Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Nuclear Materials 337–339 (2005) 65–68
journal of nuclear materials
www.elsevier.com/locate/jnucmat

On dust in tokamak edge plasmas

S.I. Krasheninnikov [a,*], T.K. Soboleva [b], Y. Tomita [c], R.D. Smirnov [d], R.K. Janev [c]

[a] *Jacobs School of Engineering, Department of Mechanical and Aerospace Engineering, University of California at San Diego, Engineering Building II, room 474, 9500 Gilman Drive, La Jolla, CA 92093-0411, USA*
[b] *UNAM, Mexico, DF, Mexico and Kurchatov Institute, Moscow, Russia*
[c] *National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[d] *The Graduate University for Advanced Studies, Toki, Gifu 509-5292, Japan*

Abstract

We study the dust particle dynamics in tokamak edge plasmas, with special emphasis on dust particle transport in the sheath and plasma recycling regions. The characteristics of this transport have been examined for both smooth and corrugated wall surfaces. The implications of dust particle transport in the divertor region on the core plasma contamination with impurities have also been examined.

PACS: 52.40.Hf; 52.25.Vy; 52.55.Fa
Keywords: Dust particles; Sheath; First-wall; Edge plasma; Impurity transport

1. Introduction

The presence of substantial amounts of dust has been observed on the first walls of fusion devices (see papers [1–7] and the references therein). Although, the impact of dust on plasma parameters in current fusion devices is not clear [8,9], dust in burning plasma experiment may cause a significant safety threat (see Ref. [7] for details).

In present, the predominant formation mechanisms of dust particles in fusion devices are not known. Nevertheless, in Ref. [10] was shown that once dust particle comes from the wall into tokamak edge plasma it accelerates by plasma flows and can quickly traverse distances comparable to tokamak radii before being disintegrated due to erosion caused by the interactions with plasma. As a result, the dust deposition areas on the wall structures can be spread far away from the origin of the dust.

In this paper we review the results of Ref. [10] and consider some new aspects of dust dynamics in tokamak plasmas, which we found from numerical modeling of dust particle motion. We also discuss an impact of dust on core plasma contamination with impurity. Following [10] we assume that dust density is rather small and ignore collective phenomena associated with the dust [11,12].

* Corresponding author. Tel.: +1 858 822 3476; fax: +1 858 534 7716.
E-mail address: skrash@mae.ucsd.edu (S.I. Krasheninnikov).

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2004.09.031

2. Forces and dust dynamics in the vicinity of smooth surface

In order to simplify our estimates we will assume that electron, T_e and ion, T_i, temperatures are close to $T_i \approx T_e = T \sim 10$ eV and plasma density is about 3×10^{13} cm^{-3}. These values are rather typical for tokamak divertor plasmas.

In tokamak edge plasma the dust particle is usually negatively charged, $-eZ_d$, to maintain the ambipolarity of plasma flux onto dust particle (here e is the elementary charge). For spherical particle Z_d can be estimated as follows: $Z_d = \Lambda T r_d/e^2$ where r_d is the radius of dust particle and Λ is the numerical coefficient which rather weakly depends on the ratio of electron to ion temperatures, relative motion of plasma and dust, magnetic field effects, and location of dust particle with respect to the surface. In our estimates we will take $\Lambda \approx 3$.

We will assume that dust particle has no internal structure and its motion is determined by the momentum balance equation

$$M_d \frac{d\mathbf{V}_d}{dt} = \mathbf{F}, \tag{1}$$

where $\mathbf{V}_d$ and M_d are the velocity and mass of dust particle, and $\mathbf{F}$ is the total force acting on it.

The analysis of the forces acting on a micron scale dust particle in fusion plasmas shows [10] that the dominant ones are: the electric force $\mathbf{F}_E = -eZ_d\mathbf{E}$ (where $\mathbf{E}$ is the electric field strength) and the plasma-dust particle friction force $\mathbf{F}_{\text{fric}} = \varsigma_F \pi r_d^2 M_i n V_i \mathbf{V}_p$, where n and $\mathbf{V}_p$ are the plasma density and hydrodynamic velocity (we assume that $V_p > V_d$), M_i and $V_i = \sqrt{T/M_i}$ are the ion mass and thermal speed, and $\varsigma_F \sim 10$ is a numerical factor accounting for the difference of electron and ion temperatures, the ratio of V_p/V_i, as well as the magnetic field effects.

Dust motion in the direction perpendicular to the wall is determined by (a) normal component of the friction force caused by the plasma flow along the magnetic field lines to the wall, which pushes dust toward the wall and (b) sheath electric field, which repulses negatively charged dust from the wall. For a typical case of a small inclination angle, α, of magnetic field to the wall surface (see Fig. 1) normal component of friction force in the vicinity of the wall can be estimated as $\alpha F_{sh} \approx$ const. where $F_{sh} = \varsigma_F n T \pi r_d^2$.

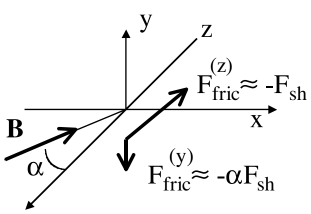

Fig. 1. Orientation of magnetic field, plasma flows, and friction forces.

Therefore, net impact of friction and electric forces on normal $(-y)$ component of dust velocity can be described with effective potential

$$U_d(y) = \alpha F_{sh} y + \Lambda \frac{r_d T}{e} \varphi(y), \tag{2}$$

where $\varphi(y)$ is the electrostatic potential. Electrostatic potential is of the order of T/e at the wall and falls quickly outside the sheath, $y > \rho_i$, where ρ_i is the ion gyroradius. As a result the potential $U_d(y)$ has a minimum at $y = y_{\min}(r_d)$, where electric force balances normal component of friction force. The motion of dust particle, confined by the potential $U_d(y)$, can exhibit damping oscillations. Small amplitude oscillations in the vicinity of $y_{\min}$, are characterized by the frequency

$$\Omega_d^2 = \frac{1}{M_d} \frac{d^2 U_d}{dy^2}\bigg|_{y=y_{\min}} \sim \left(\frac{\alpha F_{sh}}{M_d \rho_i}\right)^{1/2}. \tag{3}$$

For $n = 3 \times 10^{13}$ cm^{-3}, $T = 10$ eV, $\alpha \sim 0.1$, and the mass density of dust particle $\tilde{\rho}_d \sim 2$ g/cm^3, we find that Ω_d is much larger than dumping rate and much smaller than the charging frequency, which are respectively of the order of ~ 1 s^{-1} and $\sim 10^{11}$ s^{-1} for the above dust and plasma parameters.

While in y direction the friction force can be balanced by the electric force, in the directions along the wall the electric field is only due to wall and plasma inhomogeneities (which we assume to be small here), but the friction force remains strong due to plasma flow along oblique magnetic field lines and ion diamagnetic and $\mathbf{E} \times \mathbf{B}$ flows in x-direction. Within the sheath, the ion flow velocities of both z- and x-directions are close to V_i, which gives the following estimate for the z- and x-components of the friction force

$$F^{(z)}_{\text{fric}} \sim F^{(x)}_{\text{fric}} \sim F_{sh}. \tag{4}$$

At distances from the wall larger than ρ_i, the diamagnetic ion flow velocity and, consequently, $F^{(x)}_{\text{fric}}$ significantly decrease, while the component $F^{(z)}_{\text{fric}}$ remains strong everywhere in the plasma recycling region.

The unbalanced force (4) causes acceleration and motion of dust particle along the wall in both toroidal and radial directions. Since the force (4) is proportional to the plasma pressure such acceleration is particularly strong within some toroidally symmetric strip located close to the separatrix striking point where the plasma pressure is the highest. However, the poloidal acceleration causes poloidal motion of the dust particle, which pushes it out of this region. Assuming that the acceleration acts along a distance of length ℓ, we can estimate the magnitude of radial, $V_d^{(x)}$ and toroidal, $V_d^{(z)}$, velocity components that dust particle gains during the time it moves along that distance

$$V_{\mathrm{d}}^{(x)} \sim V_{\mathrm{d}}^{(z)} \sim V_{\mathrm{d}}^{(\ell)} \equiv V_{\mathrm{i}}\left(\frac{\varsigma_F M_{\mathrm{i}} n}{\tilde{\rho}_{\mathrm{d}}}\frac{\ell}{r_{\mathrm{d}}}\right)^{1/2}. \tag{5}$$

For $\tilde{\rho}_{\mathrm{d}} \sim 2\ \mathrm{g/cm^3}$, $n = 3\times10^{13}\ \mathrm{cm^{-3}}$, $T = 10$ eV, $\ell \sim 1$ cm and $r_{\mathrm{d}} \sim 3\times10^{-4}$ cm from Eq. (5) we find $V_{\mathrm{d}}^{(\ell)} \sim 3\times10^3$ cm/s. This velocity is so large that if dust particle would move with such velocity toward the wall it would penetrate through the sheath and hit the wall. In case when dust particle is reflected back after hitting the wall it can fly into the plasma volume at fairly large distance, L_{flight}.

3. Dynamics of dust particle in the vicinity of corrugated surface

As we have seen in the preceding section, the dust particle confined in the sheath region and accelerated by plasma flows can move along the surface with a very high speed. However, even rather small corrugation of the surface can cause an increase of the amplitude of particle oscillations in the potential well and even to fly out from the sheath region.

In Ref. [10] an example of sinusoidal long wavelength corrugation of wall surface in x-direction was analyzed for the case of a small amplitude, h_{s}, of corrugation, $h_{\mathrm{s}} \ll \rho_{\mathrm{i}}$. In this case particle dynamics in the vicinity of the minimum of effective potential $U_{\mathrm{d}}(y)$ can be described by the equations

$$\frac{\mathrm{d}^2 y_{\mathrm{d}}}{\mathrm{d}t^2} = -\Omega_{\mathrm{d}}^2(y_{\mathrm{d}} - y_{\min}(x)), \quad \frac{\mathrm{d}^2 x_{\mathrm{d}}}{\mathrm{d}t^2} = \frac{F_{\mathrm{fric}}^{(x)}}{M_{\mathrm{d}}}, \tag{6}$$

where $y_{\min}(x) = \bar{y}_{\min} + h_{\mathrm{s}}\sin(k_{\mathrm{s}}x)$ ($k_{\mathrm{s}}\rho_{\mathrm{i}} \ll 1$, k_{s} is the corrugation wave number) describes the variation of the location of minimum of potential $U_{\mathrm{d}}(y)$ due to wall surface corrugation, $y_{\mathrm{s}}(x) = \bar{y}_{\mathrm{s}} + h_{\mathrm{s}}\sin(k_{\mathrm{s}}x)$. In [10] it was shown that due to acceleration of dust particle along x-direction the resonance $k_{\mathrm{s}}V_{\mathrm{d}}^{(x)} = \Omega_{\mathrm{d}}$ occurs at time $t_{\mathrm{res}} \approx \Omega_{\mathrm{d}}M_{\mathrm{d}}/k_{\mathrm{s}}F_{\mathrm{fric}}^{(x)}$. For the case where $S_{\mathrm{res}} \equiv t_{\mathrm{res}}\Omega_{\mathrm{d}} \gg 1$, resonance coupling of x- and y-components of particle motion causes a strong increase of the amplitude, $\tilde{y}_{\mathrm{d}}$, of particle oscillation in the potential well, which scales as $\tilde{y}_{\mathrm{d}}(t) \approx h_{\mathrm{s}}(\pi S_{\mathrm{res}})^{1/2}$.

Here we extend the results of Ref. [10]. We will assume that $y_{\min}(x) = \bar{y}_{\min} + H_{\mathrm{s}}(x)$, where small amplitude long wavelength function $H_{\mathrm{s}}(x)$ ($|H_{\mathrm{s}}(x)| < \rho_{\mathrm{i}}$), which determines the boundary of wall surface, is not simple sinusoidal function as was assumed in Ref. [10], but random multi-harmonic function. As a result, instead of describing the motion of one dust particle, we will analyze the behavior of ensemble of dust particles. We consider particle motion in the vicinity of $\bar{y}_{\min}$ and solve equation Eq. (6) neglecting a small dependence of $F_{\mathrm{fric}}^{(x)}(x, y \approx \bar{y}_{\min})$ on both x and y, so that $M_{\mathrm{d}}v_{\mathrm{d}}^2(x) = 2xF_{\mathrm{fric}}^{(x)}(y = \bar{y}_{\min})$. We introduce the distribution function of dust particle, $f(\varepsilon, \varphi, x)$, characterizing the ensemble of dust particles by using energy/phase, $\varepsilon = (v_y^2 + \Omega_{\mathrm{d}}^2\tilde{y}^2)/2$ and $\cos(\varphi) = \Omega_{\mathrm{d}}\tilde{y}/(2\varepsilon)^{1/2}$, variables, where $\tilde{y} = y_{\mathrm{d}} - \bar{y}_{\min}$ and v_y is the particle velocity along y coordinate. After some algebra one can show that the function $f(\varepsilon, \varphi, x)$ obeys the following kinetic equation

$$v_{\mathrm{d}}(x)\frac{\partial f}{\partial x} + \Omega_{\mathrm{d}}\frac{\partial f}{\partial \varphi} \approx \frac{\Omega_{\mathrm{d}}^2 H_{\mathrm{s}}(x)}{\sqrt{2}}\sin(\varphi)\sqrt{\varepsilon}\frac{\partial f}{\partial \varepsilon}. \tag{7}$$

Expanding the function $f(\varepsilon, \varphi, x)$ as a series of powers of H_{s}: $f(\varepsilon, \varphi, x) \approx f_0(\varepsilon, x) + f_1(\varepsilon, \varphi, x) + \ldots$, where $f_j(\varepsilon, \varphi, x) \propto (H_{\mathrm{s}})^j$, from Eq. (7) in a quasi-linear approximation we find

$$\frac{\partial f_0}{\partial x} = \frac{\pi}{4}\frac{\Omega_{\mathrm{d}}^4}{v_{\mathrm{d}}^2(x)}\left|\widehat{H}_{\mathrm{s}}(k)\right|^2_{k=\frac{\Omega_{\mathrm{d}}}{v_{\mathrm{d}}(x)}}\sqrt{\varepsilon}\frac{\partial}{\partial \varepsilon}\left(\sqrt{\varepsilon}\frac{\partial f_0}{\partial \varepsilon}\right), \tag{8}$$

where $\langle H_{\mathrm{s}}^2(x)\rangle = \int|\widehat{H}_{\mathrm{s}}(k)|^2\mathrm{d}k$. Taking into account that $v_{\mathrm{d}}^2(x) \propto x$, for $\widehat{H}_{\mathrm{s}}(k \to 0) = \widehat{H}_{\mathrm{s}}(0)$, from Eq. (8) we find asymptotic expression for the averaged energy ε of dust particle $\bar{\varepsilon}(x) \equiv \langle\varepsilon\rangle$:

$$\bar{\varepsilon}(x \to \infty) \approx \frac{3\pi}{16}\frac{M_{\mathrm{d}}\Omega_{\mathrm{d}}^4}{F_{\mathrm{fric}}^{(x)}(\bar{y}_{\min})}\left|\widehat{H}_{\mathrm{s}}(0)\right|^2\ln\left(\frac{x}{\rho_{\mathrm{i}}}\right). \tag{9}$$

As a result, from Eq. (9) one finds that averaged amplitude $\langle\tilde{y}_{\mathrm{d}}^2\rangle$ of dust particle oscillations in the potential well of $U_{\mathrm{d}}(y)$ increases with x like

$$\left\langle\tilde{y}_{\mathrm{d}}^2\right\rangle \sim \frac{\alpha}{\rho_{\mathrm{i}}}\left|\widehat{H}_{\mathrm{s}}(0)\right|^2\ln\left(\frac{x}{\rho_{\mathrm{i}}}\right). \tag{10}$$

In case of large amplitude of surface wave $H_{\mathrm{s}} > \rho_{\mathrm{i}}$, due to a strong effect of centrifugal force dust particle looses confinement within the sheath region even before it reaches resonance condition $V_{\mathrm{d}}k_{\mathrm{s}} = \Omega_{\mathrm{d}}$ [10]. To study dust particle dynamics in this regime we use numerical modeling.

We solve Eq. (1) assuming that the wall is corrugated along either x or z directions and it affects the force $\mathbf{F}$. In the case where the wall is corrugated along x direction we describe the force acting on the dust particle as $\mathbf{F} = -\nabla\Phi_\perp - \nabla\Phi_\parallel \times \mathbf{e}_z$, where $\Phi_\perp(x, y) = \widehat{\Phi}_\perp(y - y_{\mathrm{s}}(x))$ and $\Phi_\parallel(x, y) = \widehat{\Phi}_\parallel(y - y_{\mathrm{s}}(x))$ describe respectively the effects of the corrugation on effective potential $U_{\mathrm{d}}(y)$ and x-component of the friction force caused by diamagnetic and $\mathbf{E}\times\mathbf{B}$ plasma flows in the sheath region. As a reasonable approximation we take $\widehat{\Phi}_\parallel(y) = F_{\mathrm{sh}}\rho_{\mathrm{i}}\times\exp(-y/\rho_{\mathrm{i}})$ and $\widehat{\Phi}_\perp(y) = \alpha F_{\mathrm{sh}}\{y + \rho_{\mathrm{i}}\exp((y_{\min} - y)/\rho_{\mathrm{i}})\}$. We also assume specular reflection of dust particle from the surface. With this model we were able to recover the main results we obtained analytically for the case of a small corrugation of the surface. For the case of large corrugation, $|H_{\mathrm{s}}(x)| > \rho_{\mathrm{i}}$, we found that dust particles, being accelerated to large speed, fly at large distance from the surface (even toward the core) and hit the wall when they are coming back due to friction force effects. Such flights can have stochastic character (see Fig. 2 for $y_{\min} = \rho_{\mathrm{i}}/2$, $H_{\mathrm{s}}(x) = h_{\mathrm{s}}\sin(k_{\mathrm{s}}x)$, $h_{\mathrm{s}}/\rho_{\mathrm{i}} = 3$, $k_{\mathrm{s}}\rho_{\mathrm{i}} = 0.3$ and

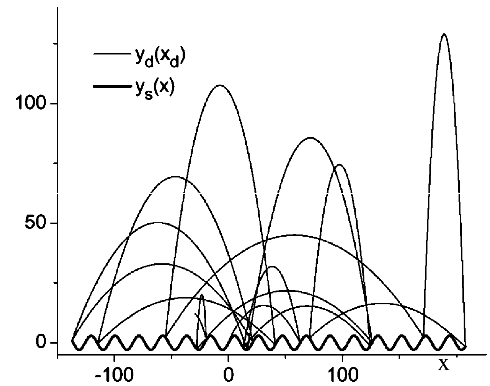

Fig. 2. Stochastic flights of dust particle over corrugated surface.

$\alpha = 0.1$) having some intermittent features. More detail report on the result of numerical modeling of dust particle motion will be published elsewhere.

4. Dust dynamics and core plasma contamination

As we saw, dust particles flights caused by wall surface corrugation can result in the motion of dust toward core and, therefore, contaminate core plasma with impurity. Assuming that the main dust particle material is carbon, we find that in each dust particle with $r_{\mathrm{d}} \sim 3\times10^{-4}$ cm and $\tilde{\rho}_{\mathrm{d}} \sim 2$ g/cm^3 there are $N_{\mathrm{C}} \sim 10^{13}$ carbon atoms. In order to maintain a constant impurity fraction, ξ_{imp}, in the core, the carbon influx through the separatrix, $\Gamma_{\mathrm{imp}}^{(\mathrm{sep})}$, should be about $\xi_{\mathrm{imp}}\Gamma_{\mathrm{H}}^{(\mathrm{sep})}$, where $\Gamma_{\mathrm{H}}^{(\mathrm{sep})}$ is the flux of hydrogenic species though the separatrix. For $\xi_{\mathrm{imp}} \sim 10^{-2}$ and $\Gamma_{\mathrm{H}}^{(\mathrm{sep})} \sim 10^{21}$ s^{-1}, we find $\Gamma_{\mathrm{imp}}^{(\mathrm{sep})} \sim 10^{19}$ s^{-1}, and it would take a flux, $\Gamma_{\mathrm{d}}^{(\mathrm{sep})} \sim 10^{6}$ s^{-1}, of dust particle to establish the required impurity influx. Assuming that dust particles penetrate to the core through an area $\sim10^5$ cm^2 and their speed is $\sim10^3$ cm/s, we find that the corresponding density of dust particles near the separatrix is $n_{\mathrm{d}} \sim 10^{-2}$ cm^{-3}. Where could this dust come from? Let us assume that dust originates at the walls of the main chamber due to plasma flux to the wall. To maintain impurity balance we have to have $\Gamma_{\mathrm{imp}}^{(\mathrm{sep})} \sim \xi_{\mathrm{imp}}\Gamma_{\mathrm{H}}^{(\mathrm{sep})} \sim Y_{\mathrm{C}}\eta_{\mathrm{dust}}\eta_{\mathrm{flight}}\Gamma_{\mathrm{H}}^{(\mathrm{sep})}$, where η_{dust} is the fraction of sputtered carbon converted into dust, η_{flight} is the dust fraction that flies to the core. Since $Y_{\mathrm{C}} \sim \xi_{\mathrm{imp}} \sim 1\%$ we have to assume that roughly $\sim100\%$ of sputtered carbon is transformed into dust and then flies to the core, which is unlikely the case. Another possibility, dust formation in the vicinity of divertor striking points, looks much more probable. Indeed, due to the strong plasma recycling in the divertor, the plasma flux to divertor targets, $\Gamma_{\mathrm{H}}^{(\mathrm{div})}$, can easily be as high as 10^{23} s^{-1} $\gg \Gamma_{\mathrm{H}}^{(\mathrm{sep})}$. Then, the impurity influx into the core caused by dust, $\xi_{\mathrm{imp}}\Gamma_{\mathrm{H}}^{(\mathrm{sep})} \sim Y_{\mathrm{C}}\eta_{\mathrm{dust}}\eta_{\mathrm{flight}}\Gamma_{\mathrm{H}}^{(\mathrm{div})}$, can be established for $Y_{\mathrm{C}} \sim 3\%$, $\eta_{\mathrm{dust}} \sim 3\%$ and $\eta_{\mathrm{flight}} \sim 10\%$, which looks very feasible [10].

Thus we conclude that due to acceleration by plasma flows in the vicinity of material surface, dust particles can acquire very high speeds ($\sim10^3$ cm/s and higher). Interactions of dust particles with corrugated surface can cause an escape of dust particle to from near wall region and flights toward tokamak core. It is likely that dust formation in and transport from divertor region can play an important role in core plasma contamination. However, even then, dust particle density around the separatrix is $\sim10^{-2}$ cm^{-3}, which makes it difficult to diagnose.

Acknowledgment

Work is supported in part by the U.S. DOE.

References

[1] R. Behrisch, P. Borgsen, J. Ehenberg, et al., J. Nucl. Mater. 128&129 (1984) 470.
[2] J. Winter, Plasma Phys. Control. Fus. 40 (1998) 1201.
[3] J. Winter, G. Gebauer, J. Nucl. Mater. 266–269 (1999) 228.
[4] C.H. Skinner, C.A. Gentile, M.M. Menon, R.E. Barry, Nucl. Fus. 39 (1999) 1081.
[5] A. Sagara, S. Masuzaki, T. Morisaki, et al., J. Nucl. Mater. 313–316 (2003) 1.
[6] J.P. Sharpe, V. Rohde, A. Sagara, et al., J. Nucl. Mater. 313–316 (2003) 455.
[7] G. Federici, C.H. Skinner, J.N. Brooks, et al., Nucl. Fus. 41 (2001) 1967.
[8] D.H.J. Godall, J. Nucl. Mater. 111&112 (1982) 11.
[9] K. Narihara, K. Toi, Y. Hamada, et al., Nucl. Fus. 37 (1997) 1177.
[10] S.I. Krasheninnikov, Y. Tomita, R.D. Smirnov, R.K. Janev, Phys. Plasmas 11 (2004) 3141.
[11] V.N. Tsytovich, Physics-Uspekhi 40 (1997) 53.
[12] P.K. Shukla, Phys. Plasma 8 (2001) 1791.