Modelling and Diagnostics of Hypervelocity Dust Particles in a Tokamak

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Dust is produced in tokamaks by energetic plasma-surface interactions. It is expected that during the plasma discharge most of the dust particles concentrate in the low density and low temperature region between the last closed magnetic surface (LCMS) and the vessel wall where a mixture of neutral gas, multi-species tenuous plasma and micro particulate of various composition is present. To improve diagnostic techniques and gain an understanding of dust behaviour it is useful to isolate dominant effects and use simplified constraints to analyse the motion of a test particle in given force fields and interaction with boundary and plasma facing components (PFC).

Recent observations of craters found on an electrostatic probe in FTU [1] are compatible with the impact of hyperfast (v≥1.5 km/s) micrometric dust particles. In order to detect such particles, a new concept electro-optic probe was designed and realized [2, 3, 4] by IFP-CNR in Milan and ENEA together with a numerical code for the modelling of the dust dynamics. In this work a study is presented, applied to the specific case of the FTU tokamak, of the motion of a micrometric dust test particle and of the acceleration mechanisms that can take such particle to hypervelocity regimes.

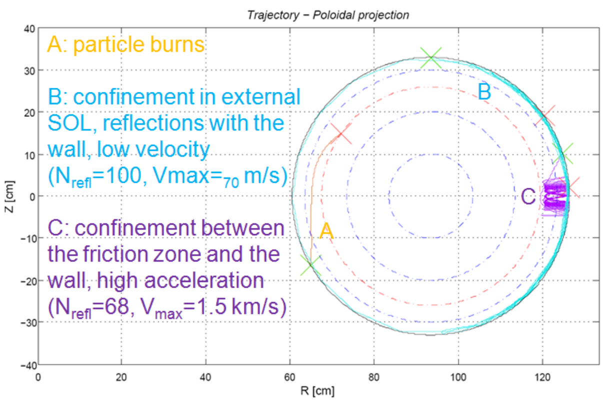

Figure 1: Example of three different types of trajectories obtainable as results from simulations depending on the initial conditions (case of no evaporation).

Since the PFC in FTU is mainly stainless steel, the dust particle is assumed to be ferromagnetic (iron); the dust grain is assumed to be spherical for simplicity. A new significant element introduced in the test particle model is the consideration of experimental plasma density and temperature profiles with the inclusion of one or more impurity ions consistent with Z_{eff}.

The impurity density profile is described by the Zagorski-Romanelli model [5] and the charge of the impurity population is described using the average ion method [6], in which only one species is considered with an average charge depending on plasma temperature, i.e. on the position inside the tokamak. Once the dust grain wins the adhesion force with the wall, its dynamics is governed by several forces;

$$m_d \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \sum_i m_i n_i \pi a_d^2 v_{ti} \zeta_i(u_i, \chi)(\mathbf{v}_i - \mathbf{v}) + \mu \nabla B + q_d(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}) - \mathbf{v}\frac{\mathrm{d}m_d}{\mathrm{d}t} + m_d \mathbf{g} + \Theta_{wall} \quad (1)$$

namely the drag force due to plasma flow, the force due to magnetic dipole interaction, the electric and the Lorentz force, a "mass ablation induced force" due to mass variation, the gravity force and a term for elastic reflections on the tokamak wall; here m_d, a_d and μ are the dust grain mass, radius and magnetic dipole moment; m_i, n_i and v_{ti} are the mass, number density and thermal velocity of the i-th plasma species, $\mathbf{v}_i$ is the flow velocity of the plasma species and $\zeta_i(u_i, \chi)$ [7] is a complicated function of both the normalized relative velocity $u_i = |\mathbf{v}_i - \mathbf{v}|/v_{ti}$ and the dust surface potential $\chi = -e\phi/T_e$ (normalized to electron temperature T_e).

The most important force, after the inertial effect, is the drag force. The drag force is due to the friction of the dust particles with all the species composing the plasma; however the main contribution is given by plasma ions, while the effect of electrons and neutrals can be neglected because of the small mass and of the low density and temperature, respectively; the contribution of impurity atoms can be important in some cases. The drag force is due to two different physical processes, namely the collection of particles and the electrostatic scattering (since a dust particle in a plasma is electrically charged).

Depending on dust temperature, i.e. on its position inside the tokamak plasma, two other forces can be very effective: the magnetic dipole force $\mu\nabla B$ at low temperatures (near the wall) and the "mass ablation induced force" $-\mathbf{v}\frac{\mathrm{d}m_d}{\mathrm{d}t}$ due to the mass loss flux [8], $\frac{\mathrm{d}m_d}{\mathrm{d}t} = \pi a_d^2 m_I \Gamma_{net} \simeq \pi a_d^2 m_I \Gamma_{sub}$, where the net mass flux Γ_{net} from/to the dust particle is substantially equal to the evaporation/sublimation flux Γ_{sub} when the dust temperature is high (external plasma core), while its effects are negligible when the dust temperature is low, and m_I is the mass of the ejected particles. This two forces depend strongly on the material composing dust: the first one is obviously important only for ferromagnetic materials, the second one is more important for those materials, such as iron, that exhibit a liquid phase at relatively low temperatures, while for materials such as carbon (no liquid phase) or tungsten (high melting temperature) this force is orders of magnitude lower.

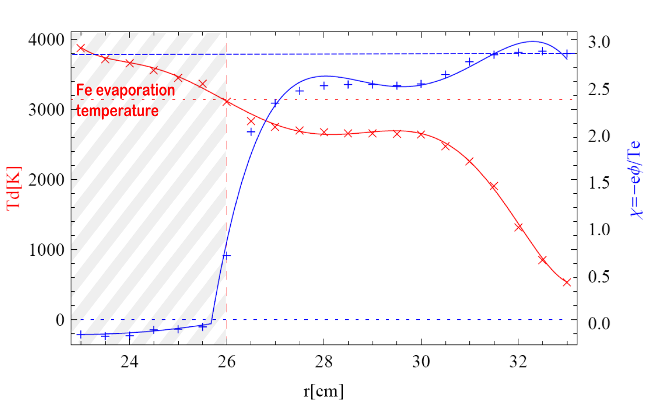

Figure 2: The dust temperature T_d (in red) and the dust surface potential χ (in blue) as a function of the tokamak minor radius r. The crosses are numerical results from (2), the lines are polynomial fits.

The forces acting on the dust grain depend in a nonlinear way on both dust surface electric potential χ and dust temperature T_d, i.e. these two quantities have to be determined carefully. In the present work the dust surface potential and the dust temperature are determined simultaneously from equilibrium conditions, namely the ambipolarity condition $I_{tot} = 0$ and the thermal equilibrium condition $W_{tot} = 0$, since some currents considered (the thermionic emission current I_{th}) depend on T_d and the energy fluxes consistent with the currents considered depend on χ. As a news with respect to the first version of the code, in which only I_i and I_e, respectively the ion and electron OML currents [9] where considered, and the only cooling flux was W_{bb}, due to black body radiation, giving a constant potential $\chi = 2.8$ (negative charge), here also a thermionic emission current I_{th} [10] and secondary electron emission [11] current I_{see} are considered, and the cooling fluxes W_{sub} due to dust sublimation/evaporation and W_{th}, W_{see} the energy fluxes consistent with the respective currents are added. The system

$$\begin{cases} I_{tot}(\chi, T_d) = I_e + I_i + I_{see} + I_{th} = 0 \\ W_{tot}(\chi, T_d) = W_e + W_i + W_{see} + W_{th} + W_{bb} + W_{sub} = 0 \end{cases} \tag{2}$$

has to be solved numerically. As a result (see fig. 2) the dust potential lowers entering the plasma, due to the rising of both plasma and dust temperature, eventually going to zero and changing sign, sensibly affecting the drag force. Numerical simulations are produced in order to study the dynamics of the dust particle. In absence of the evaporation flux, the main acceleration mechanism is the combination of the drag force and reflections with the tokamak wall, due to inertial effects, that can result in hypervelocity ($v \geq 1.5$ km/s) within $N_{refl} \sim 60$ reflections with the wall. The maximum velocity reached by the particle grows approximately as $N_{refl}^{1/2}$. The contribution of the impurity ions to the total drag force was studied with both analytical and numerical methods, showing that, depending on the atomic species and density of the impurity considered, the final velocity of a dust particle can increase of a few 10% with respect to the case with the same initial conditions and and no impurity; this contribution is limited but not negligible. When the evaporation flux is considered, the dynamics changes substantially, since the mass ablation induced force, proportional to dust velocity, becomes the dominant term in the equation of motion, resulting in an exponential growth of velocity and reaching the hypervelocity regime in $N_{refl} \sim 3$ if the dust grain crosses the LCMS. The new Electro-Optical probe designed and built by IFP-CNR and ENEA in order to detect hyperfast micrometric dust grains will be soon operative on FTU. The diagnostic concept of the EO probe is based on the coincidence between an electric signal and an optical signal, collected by optical fibres, that a hyperfast dust grain would produce upon collision with an active part (a tungsten tip) resulting in an ionization impact with the formation of an optically emitting plasma. Experimental results [12] show that this can happen for micrometric iron particles impacting on a tungsten target with a velocity $v \geq 1.5$ km/s. The shape of the tungsten 3.0 X 1.8 mm^2 active part has been implemented in the simulation code, and simulations dedicated to the diagnostic case have been produced, showing the existence of trajectories colliding with the probe with a velocity sufficient for impact ionization, both in the case of drag force driven and sublimation driven trajectories.

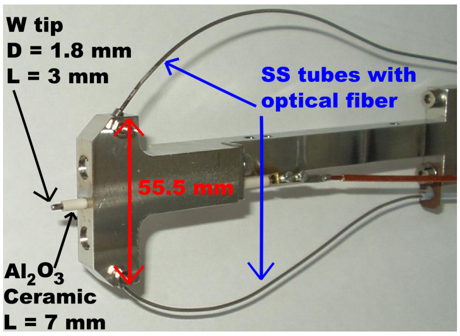

Figure 3: Photograph of the EO probe realized in Milan.

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