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Modelling of W dust dynamics related to radiating plasmoid formation

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Introduction

Transient Impurity Events (TIEs) leading to intense radiation spikes are often observed in tokamaks with tungsten (W) lined (e.g. JET with the ITER-Like Wall, ILW), namely after disruptions [1-2]. In JET-ILW, TIEs with a significant increase of radiated power (1.5 MW on average) could be associated to polluting W ions resulting from dust ablation [2]. The interpretation of these events brings to key questions concerning the total amount of dust mobilised from the Plasma Facing Components (PFCs) and the tokamak vessel, and the contribution of the dust ablated mass to the contamination of the plasma. Here we present some applications of the dust trajectory code DUSTTRACK [3-4] to the qualitative and quantitative description of the mobilisation and fate of bunches of isolated spherical W dust particles, subject to dynamic interactions with the Scrape-Off Layer (SOL) plasma and the tokamak first-wall. Particular emphasis is placed on the thermodynamic phase transformations of W dust particles which can bring to their full ablation. The neutral ablated cloud thus formed, interacting with the surrounding plasma, ionises leading to a high dense and cold W plasma, plasmoid in the following, probably responsible of TIEs. Inspired by researches on the injection of fuel pellets in tokamaks [5-6], an MHD model has been developed to study the time evolution of the shape of the radiating W plasmoid and it is here described.

Case studies

A first investigation of W dust mobilisation, redeposition and plasma pollution in JET-ILW is carried out by considering a relatively large number (~100) of 10 μm-radius W particles launched from the divertor louvres and dome (fig.1a). A parametric classification of the more likely sources of radiating plasmoids is pursued considering the percentage of particles reaching temperatures at which ablation is significant (i.e. from W melting temperature).

As study case we consider a JET-ILW background plasma corresponding to that of shot #82806 at t=55-56 s, that has been extensively used to validate the DUSTTRACK code against DTOKS [4]. The general characteristics of the dust particles trajectories are mainly determined by: the friction force with the ions of the plasma, the evolution of dust charge and thermodynamic state [3] and the complicated reflection pattern from the wall.

The case of W dust mobilised from divertor louvres of tiles 4 and 6 is shown in fig.1b.

Apparently very few particles cling the wall surface escaping from the divertor legs and finally contaminating the plasma and/or producing TIEs.

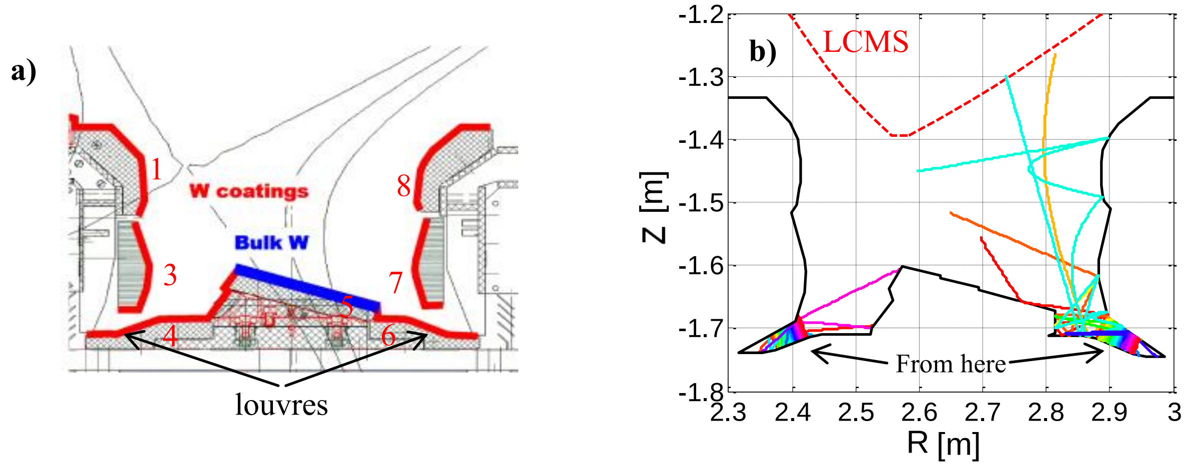

Fig.1: (a) Schematic of JET-ILW divertor. Reprinted from [7]. (b) Poloidal trajectories of W dust particles (202) launched vertically from louvres of tiles 4 and 6 at 9 m/s.

On the contrary, W dust particles mobilised from the dome (tile 5, fig.1a) of the divertor impinge on vertical tiles 7 and 8 (fig.2a) and a fraction >30% (fig.2b) is reflected and the particles invade the private flux region or go toward the Last Closed Magnetic Surface (LCMS), reaching temperatures at which they ablate (through surface evaporation and eventually boiling), possibly responsible for TIEs. In this respect it appears that a suitable baffle on tile 8 could deflect the dust away from separatrix. It is interesting that a few W particles creeping out the divertor, in the low density SOL, can reach rather high speed ~130 m/s (fig.2c).

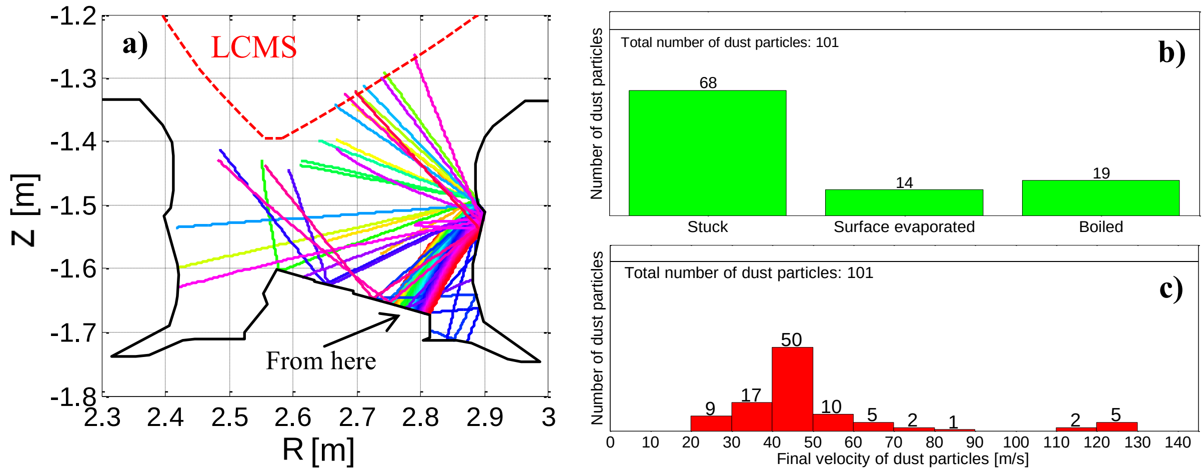

Fig.2: (a) Poloidal trajectories of 10 μm-radius W dust population (101 particles) mobilised vertically from JET-ILW dome (tile 5) at 9 m/s. Histograms of their: (b) reasons of death (adhesion to the wall, surface evaporation, surface evaporation + boiling), (c) final velocities.

The state transition from solid to molten and eventually gaseous state of the W particles, assumed spherical also when molten (since the Weber number We~0.18 is <1), proceeds with mass ablation and regression of the initial solid radius R_d. Ablation occurs through surface evaporation ($\propto p_v(T_d)$ dust vapour pressure, function of dust temperature T_d) and boiling. The neutral ablating mass progressively ionises interacting with the ambient plasma and a high dense and cold W plasmoid is formed. As expected, the development of a full ablation model for W dust particles describing all these phenomena is quite challenging, even though it can be built upon the existing knowledge of pellet injection physics [5-6]. Here we consider interesting to inspect the role of the MHD behaviour of a W plasmoid. In particular, we obtain from a dimensional analysis the basic scaling of the cloudlet dimensions across and parallel to tokamak magnetic field $\vec{B}$.

MHD constraints on W plasmoid expansion

The time evolution of the W plasmoid shape is essentially governed by $\vec{J}\times\vec{B}$ forces due to the tokamak $\vec{B}$ field and the hydrostatic pressure, much higher than ambient plasma pressure. Starting from the inviscid, resistive MHD momentum equation (in cgs units) we have:

$$\frac{d\left(u_{//}\vec{b}+\vec{u}_{\perp}\right)}{dt}=-\frac{1}{\rho_m}\nabla p-\frac{\sigma B^2}{\rho_m c^2}\left(\vec{u}_{\perp}-\vec{v}_E\right) \qquad (1)$$

where $\vec{u}$, p, ρ_m and σ are: the velocity (parallel, //, and perpendicular, $\perp$, to $\vec{b}=\vec{B}/B$) field, pressure field, density (supposed constant) and electric conductivity of W plasmoid and $\vec{v}_E$ is $\vec{E}\times\vec{B}$ drift velocity. The expansion of the plasmoid can be described following the evolution of the Lagrangian displacement $\vec{\ell}(s_0,t)=\ell_{//}\vec{b}+\vec{\ell}_{\perp}$ such that $\vec{u}=d\vec{\ell}(s_0,t)/dt=\partial\vec{\ell}(s_0,t)/\partial t$, where s_0 is the curvilinear abscissa along the magnetic field line. Assuming $\left|\vec{\ell}\right|<<R_0$ tokamak major radius, we consider local cylindrical coordinates having the Centre-of-Mass (COM) of the plasmoid as the origin of the reference frame (fig.3a). Further assumptions are: (i) the pressure field is transformed to Lagrangian variables as $p\left(\ell_{\perp},\varphi,\ell_{//}\right)=p(\rho)$ where $\rho=\sqrt{\ell_{\perp}^2+\ell_{//}^2}$, (ii) $\frac{dp}{d\rho}\cong-\frac{p_{v,W}\left(T_d\right)}{\rho}$ and (iii) only the toroidal component of $\vec{B}$, that is $\frac{B_0 R_0}{R}\vec{e}_{//}$ with $B_0=B(R_0)$, is taken into account. Eq.1 leads to the following dynamical model ($C_S=\sqrt{p_{v,W}/\rho_m}$ is the sound velocity of W plasma) at the leading order in ρ/R:

$$\begin{cases} \dfrac{d^2\ell_{//}}{dt^2} \cong C_S^2 \dfrac{\ell_{//}}{\ell_\perp^2 + \ell_{//}^2} & (2) \\ \dfrac{d^2\ell_\perp}{dt^2} + \dfrac{\sigma B_0^2 R_0^2}{\rho_m c^2 R^2} \dfrac{d\ell_\perp}{dt} \cong C_S^2 \dfrac{\ell_\perp}{\ell_\perp^2 + \ell_{//}^2} + \dfrac{\sigma B_0 R_0 E_0}{\rho_m c R} & (3) \end{cases}$$

The result of the numerical integration of eqs.2-3 for a W plasmoid in JET-ILW at different times (fig.3b) shows the elongated-along $\vec{B}/B$ shape, recurrent in fuel pellets literature [6]. In order to understand this behaviour, we apply a dimensional analysis of RHS of eq.3, which leads to the comparison of $\left[C_S^2 \dfrac{\ell_\perp}{\ell_\perp^2 + \ell_{//}^2}\right]$ with $\left[\dfrac{\sigma B_0 R_0 E_0}{\rho_m c R}\right]$. When these two terms become of the same order and anisotropy of the plasmoid pressure field in directions parallel and perpendicular to $\vec{B}$ ($\ell_\perp << \ell_{//}$) is assumed, the scaling $\ell_{//} \propto \sqrt{R\ell_\perp}$ follows. This scaling law obtained here from MHD principles is in agreement with what is used in models for ablation of fuel pellets in tokamaks (i.e. in the Neutral-Gas-Plasma Shielding model), based on single particle drifts [5,6].

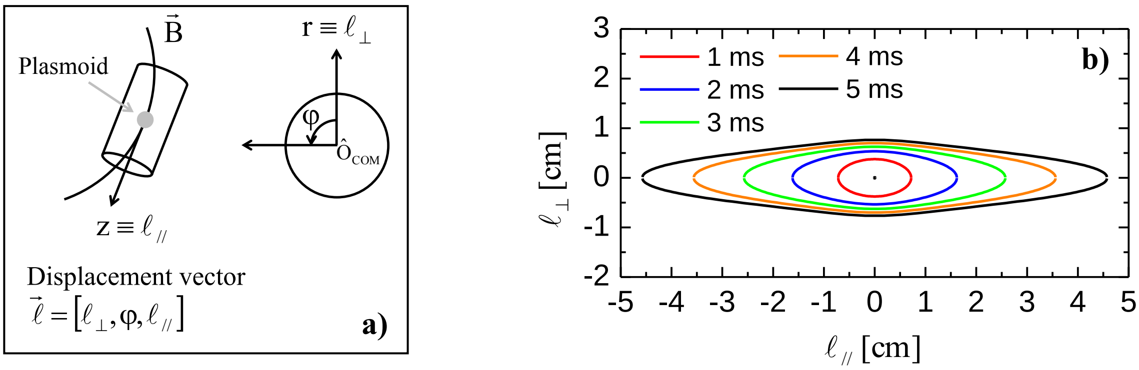

Fig.3: (a) Reference frame of the model for the evolution of W plasmoid shape. (b) Numerical solution of eqs.2 and 3 which gives the time evolution of a 100 μm-radius W plasmoid at 6000 K in JET-ILW tokamak at $R = 320$ cm ($R_0 = 296$ cm and $B_0 = 2000$ gauss). $E_0 \cdot c = 0.01 \cdot C_s \cdot B_0$.

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