High heat loads producing large size dust particles in Alcator C-Mod

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Abstract

Rounded dust particles such as spheres and splashes were collected in the Alcator C-Mod tokamak. They are the result of high heat loads applied on the leading edges of plasma facing components. Disruptions destabilize these regions and molten material droplets are emitted through the vacuum chamber. The formed dust particles are characterized by an average size larger than in any other metal tokamak. To reduce their production, a slight rotation of the lower outer-divertor sectors was done in order to shadow every leading edge by the upstream neighboring sector. As expected, less dust particles were produced.

Introduction

Plasma facing units in the ITER divertor will be formed with chains of tungsten monoblocs (MB). One identified key issue is linked to the MB misalignment. Under cycles of heat loads and transient high heat loads, the MB leading edges could be melted and induce emission of molten W splashes and droplets [1-4]. Resulting surface damage could compromise plasma operation by changing the W mechanical structure and by reducing the MB lifetime.

One effect of the tile misalignment was evidenced in the full-metal tokamak, Alcator C-Mod [5]. During plasma operation, camera videos have shown an over-light emission of various leading edges of plasma facing components (PFCs). These over-heated regions were destabilized during disruptions and led to the emission of molten material droplets through the vacuum chamber. Resulting typical rounded dust particles such as splashes and spheres were collected after 2007 and 2015 plasma campaigns. Their characteristics are presented in this paper as well as the solution adopted to reduce their production.

Dust collection in Alcator C-Mod and analyses

Alcator C-Mod is a molybdenum (Mo) tokamak divided in 10 toroidal sectors (named AB, BC .... JK). A toroidal row of tungsten (W) tiles was inserted in 2007, in the strike point region of the lower outer-divertor and removed in 2010. Before the 2015 plasma campaign, the 10 outer divertor modules were rotated by ~ 1° to avoid damages on Mo tile edges. The vacuuming technic with HEPA filters was used to collect dust on each surface sector. Elemental compositions were established by energy dispersive X-ray spectroscopy (EDS). Metallic and insulator debris (Al, Fe, Ti, Cu, Si, Ca, K…) were eliminated from the study of morphologies and sizes. Only dust in Mo, W and boron (B) resulting from the wall/PFC boronization were selected. Some large particles were transferred on the surface of a fresh resin. After solidification, this resin was polished to study the dust cross-section composition. Size distributions were established on scanning electron microscopy (SEM) images with a software providing known contours (sphere, ellipse) for spherical and elongated particles. For irregular shaped particles, the contour was hand-drawn and the software provided the equivalent diameter of the smallest circle in which the projection of all the particle contours could be circumscribed.

Compositions, morphologies and sizes

The dust sample shown Fig. 1-a) is mainly composed of rounded particles (2015 campaign) in the size range, 50-180 µm. EDS mapping Fig. 1-b) shows the presence of particles in boron (greyish, uncolored for greater clarity), in Mo (red ones), an elongated W dust at the bottom of the image (bright blue) and other dusts/debris in Al (green), Fe (violet) and Ti-dominant (bluish) on the left side. Some B particles have Mo veins. Fig. 1-c) shows the cross-section of this category of particles. It shows an heterogeneous binary alloy, composed of B grains (dark matter) and a structured B- Mo (white matter) mixture as alternated white and dark layers (lamellar microstructure), characteristic of eutectic mixture (magnification Fig. 1-d)). Let us recall that at the eutectic point, as for a pure element, the liquid transforms simultaneously in two solid phases at a unique temperature (eutectic temperature), lower than the melting temperature of each component. Generally, all the analyzed B-Mo dust particles present a

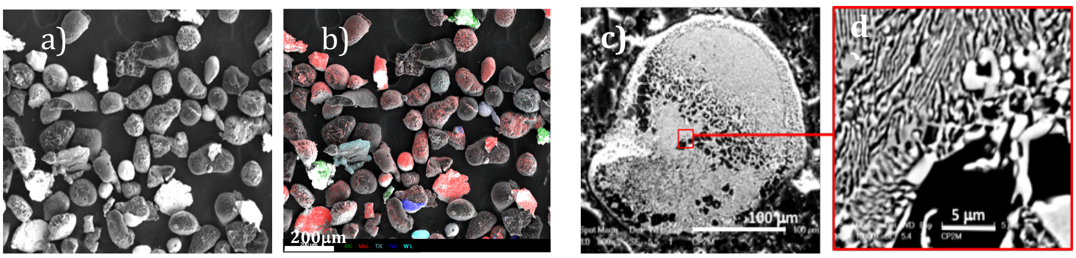

Figure 1: a) SEM image of dust produced during 2015, b) EDS mapping of the sample giving compositions (precisions in the text), c) dust particle in Mo/B alloy, d) magnification showing an alloy with eutectic microstructure

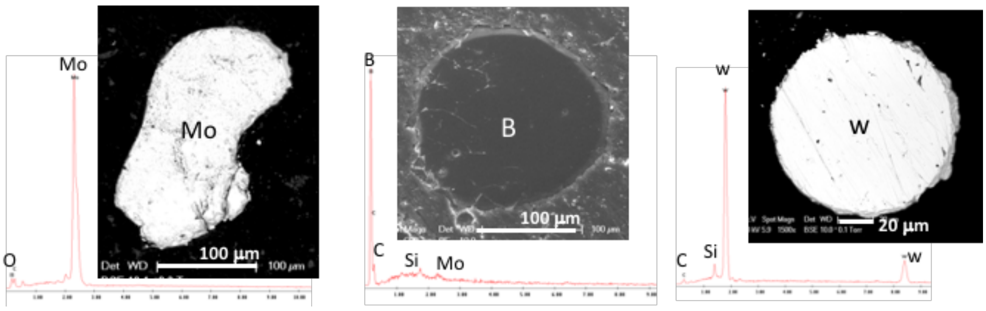

Figure 2: Cross-sections of dust particles in pure Mo (~ 250 µm size), pure B (180 µm), pure W (120 µm) and the corresponding EDS spectrum obtained in the center of each particle.

similar microstructure. Fig. 2 shows successively the cross-sections of a ~ 250 µm Mo particle (2015), a ~180 µm B sphere (2007) and a ~120 µm W sphere (2007). EDS spot-mode spectrum give the respective compositions. This investigation has confirmed the production of pure B, Mo and W rounded particles with sizes larger than 100 µm.

Fig. 3-a) gives the size distribution of Mo, B and Mo-B alloy dust coming from 2007-DE and 2007-EF sectors. The sizes of 1697 particles, which constitute just a part of the dust quantity produced in these sectors, were measured. Histograms obtained for each sector were added to provide the final size distribution. Fig. 3-b) gives the size distribution of a dust part coming from the 2015-DE sector (1065 particles). In both cases, it appears that the most probable size is ~ 50 µm and the maximum, ~ 450 µm. In both cases, the largest sizes are mostly provided by thin splash-like and thin flake-like particles (B particles) while the smallest ones are mostly rounded particles. In the final size histogram of Fig. 3-a) (Fig. 3-b)), 80% (84%) of the 2007 (2015) particles contain Mo, i.e. pure Mo and Mo-B alloy, the remaining dust being in pure B. Smaller particles than those presented Fig. 3 (< 10 µm) exist very probably. The main property of HEPA filters being to trap dust inside a mat of randomly arranged fibers, no information

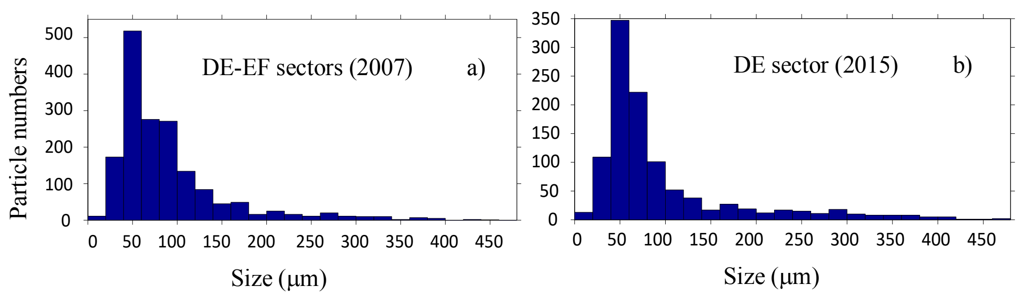

Figure 3: Size distributions of dust in Mo, B, Mo/B alloy from, a) DE-EF_2007 sectors, b) DE sector_2015

can be obtained on these small sizes. However, it is important to note that size distributions have revealed a large number of particles, larger than those already produced in other tokamaks with metal PFCs [6-7,3]

Discussion on the dust origin and production reduction

During plasma operation, camera videos have shown that during ICRF heating, over-light emission appeared on the leading edges of slot tiles, located in the upper divertor region. These tile leading edges could start to melt during the plasma phase and then be destabilized during disruptions. After disruption going upward, molten material droplets were emitted through the vacuum chamber while the tile edges still remained glowing for some time. The same scenario could also happen in the leading edges of the lower divertor sectors, which were initially misaligned. In all the cases, photos taken after plasma campaigns have shown melted tile leading edges. To suppress this damage in the lower divertor region, a slight rotation around the middle of each sector was performed at the beginning of the 2015 campaign. The goal was to shadow each sector leading edge by the upstream neighboring sector. The dust weight was measured as obtained i.e. also with dust-debris of other composition than Mo, B, W and alloys. Within this limit, the dust weight in 2015 was 3 to 6 times lower than the weight of dust taken in the same sectors in 2007. These results, added to the fact that the average energy injected in 2280 discharges in 2015 was 0.66 MJ/discharge against 2026 discharges in 2007 with 0.45MJ/discharge indicated that as expected, less dust was produced in 2015. The size distribution, which however remained similar to that of 2007, indicated the same origin mechanism.

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References

[1] B. Bazylev, *et al*., Phys. Scr. T138, 014061 (2009)
[2] R. A. Pitts, *et al*., Nucl. Mater. Energy 12, 60 (2017)
[3] A. Baron-Wiechec *et al*., Nucl. Fusion 55, 113033 (2015)
[4] M. De Angelis *et al*., J. Nucl. Mater. 463, 847 (2015)
[5] C. Arnas, *et al*., Nucl. Mater. Energy 11, 12 (2017)
[6] V. Rohde, *et al*., Phys. Scr. T138, 014024 (2009)
[7] N. Endstrasser *et al*, Phys. Scr. T145, 014021 (2011)