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Modification of adhered dust on plasma-facing surfaces due to exposure to ELMy H-mode plasma in DIII-D

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ABSTRACT

Transient heat load tests have been conducted in the lower divertor of DIII-D using DiMES manipulator in order to study the behavior of dust on tungsten Plasma Facing Components (PFCs) during ELMy H-mode discharges. Samples with pre-adhered, pre-characterized dust have been exposed at the outer strike point (OSP) in a series of discharges with varied intra-(inter-) ELM heat fluxes. We used C dust because of its high sublimation temperature and non-metal properties. Al dust as a surrogate for Be and W dust were employed as relevant to that in the ITER divertor. The poor initial thermal contact between the substrate and the particles led to overheating, sublimation and shrinking of the carbon dust, and wetting induced coagulation of Al dust. Little modification of the W dust was observed. An enhanced surface adhesion and improvement of the thermal contact of C and Al dust were the result of exposure. A *post mortem* "adhesive tape" sampling showed that 70% of Al, <5% of W and C particles could not be removed from the surface owing to the improved adhesion. Al and C but not W particles that could be lifted had W inclusions indicating damage to the substrate. This suggests that non destructive methods may be inefficient for removal of dust in ITER.

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1. Introduction

Accumulation of micron-sized metal dust particles on ITER surfaces accessible for transient heating i.e. in the strike point regions on vertical divertor targets may change surface morphology, its thermal properties and composition in case Be dust from the main chamber remains attached to the W divertor surfaces. Remobilization of deposited particles from plasma facing surfaces increases chances of such particles to either burn in hot edge plasma turning into atomic deposits or move and accumulate in remote areas from where they do not remobilize and can be removed during a dedicated vented intervention. The question of particle remobilization under steady-state conditions has been discussed in [1]. This regime is relevant for either L-mode operation non compatible with the ITER high-Q_{DT} goal or for a steady state ELM-suppressed regime, see e.g. [2].

In order to achieve the performance goal $Q_{DT} = 10$, ITER is expected to operate in the high-confinement (H-) mode. Its signature is the onset of periodic Edge Localized Modes (ELMs) which collapse the pedestal and lead to abrupt expulsion of heat and particles from the core. These transients in addition to more infrequent but severe disruptions provide conditions for excessive heating of the plasma facing components (PFCs). The strongest effect can be expected on loose redeposited layers and dust with poor thermal contact to the substrate.

During ELMy H-mode operation, plasma-exposed surfaces are heated by quasi steady-state heat fluxes with short repetitive transient ELM-induced spikes. To preserve integrity of the full-W divertor in ITER and avoid both ductile-to-brittle transition and re crystallization of tungsten, its temperature has to be kept approximately in the range 400–1500 °C [3]. During ELMs, the surface temperature excursions can be of the order of 500 °C for solid W [4] and higher for loose layers or adhered particles. This cycled exposure to high heat fluxes is expected to affect particle morphology and lifetime at the surface. It may also lead to enhanced re-

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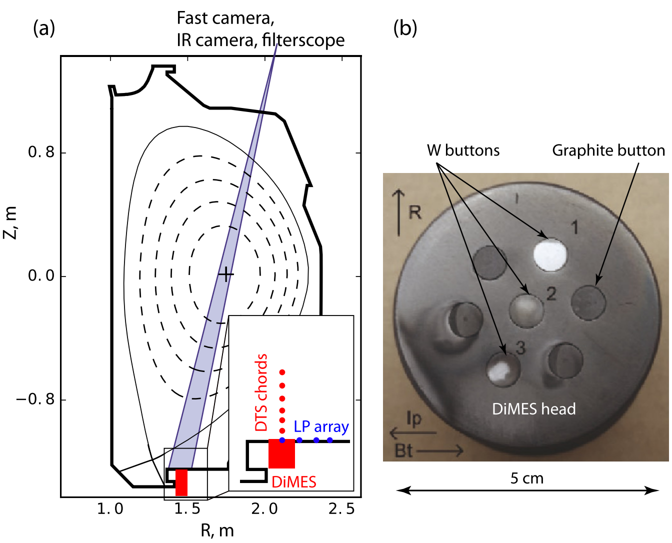

Fig. 1. (a) Poloidal cross section of the DIII-D tokamak with overlaid key plasma and material diagnostics located at different toroidal positions: Divertor Thomson Scattering system (DTS), Langmuir probes (LP), filterscope, IR- and visible-range cameras. (b) DiMES head (as removed after an experiment) with 3 tungsten buttons installed and 4 slots with graphite buttons preventing an excessive graphite erosion on leading edges. The marked B_t direction is "negative", see Table 1.

mobilization and facilitate dust removal from hot surfaces. The issue of dust remobilization under transient heat loads was first addressed in a cross-machine study reported in [5,6]. In these works, metal dust growth due to coalescence of molten grains has been shown to take place under various heat loads and exposure geometries. Experimental evidence, supported by heat transfer simulations, revealed that the metallic dust adhered to the substrate can withstand intense interaction with the plasma, while loosely attached grains in the cluster and multi-layers melt. In this paper we present the results of Al, W and C dust exposure to ELMy H-mode discharges with varying ELM power in DIII-D and show that while remobilization activity for C and Al dust is drastically different during initial exposures, the effect of sequential exposures is similar in that the dust adhesion to the surface and its resilience to heat loads improves reducing probability of remobilization and potentially complicating dust removal.

2. Experimental

A set of similar polished W specimens ⌀6 mm, with thickness t = 1.6 mm, and surface roughness $R_a = 1.6$ µm were prepared for exposure in DIII-D. DIII-D is a medium-size divertor tokamak with $R_{maj.} = 1.67$ m, $B_t \sim 2$ T and auxiliary heating up to 20 MW. It has a unique set of edge plasma and material diagnostics including: Divertor Thomson Scattering (DTS) [7], an array of Langmuir probes to monitor n_e and T_e, and Divertor Materials Evaluation System (DiMES) [8] which allows sample exposure flush with the lower divertor surface. Owing to the small size of the W samples and compact arrangement of the samples in the DiMES head, it is possible to make the exposure conditions similar for simultaneously exposed samples. An infra red (IR) camera is used to derive incident heat fluxes across the divertor, and a fast filtered visible-range imaging is available to monitor particle remobilization from DiMES, see Fig. 1. An array of filtered photomultipliers (filterscopes) with several poloidal chords measures visible emission across the divertor at sampling rate up to 100 kHz (typ. 50 kHz). Except for the fast camera which can image DiMES directly, other diagnostics occupy different toroidal locations, thus interpretation of their data requires making the basic assumption of toroidal symmetry.

The W samples were preloaded with dust particles of several types: 2–6 µm spheroidal Al, 5–25 µm spherical W, both types were previously used and described e.g. in [5], and 3–8 µm spherical C previously used in [9]. The dust deposition was performed under reproducible conditions in vacuum following a recently developed gas dynamics technique for controlled adhesion [1]. Each sample had up to 4 ⌀1 mm spots, each spot containing particles of one type, i.e. different types of dust could be deposited on one sample.

There were a total of 6 samples prepared: 1 and 2 - with Al dust, 3 - with W and C, 4 - with Al and C, 5 - with Al, and 6 - with Al and W. The samples were exposed at the outer strike point (OSP) location in the outer divertor of the DIII-D in a series of three experiments with ELMy H-mode plasmas. The samples were pre-characterized with Scanning Electron Microscopy (SEM) to document particles' and substrate morphology and map original locations of the dust grains. The SEM characterization was repeated after each experiment, and the samples were exposed again. Elemental composition of the specimens was assessed during SEM using energy dispersive X-ray spectroscopy (EDX).

After the last exposure, we attempted to assess the particle adhesion by *post mortem* removal of the exposed dust. A convenient method for sampling dust in fusion devices was used - collection with a SEM-compatible adhesive carbon tape [5]. The adhesion of the double-sided tape has been calibrated. It was first uniformly compressed between two flat metal surfaces. Then, the force that was required to separate the two surfaces divided by their area gave an estimate for the adhesive force $P_t = 0.1 \pm 0.04$ N/mm^2. Non-exposed dust spots of all types could always be entirely removed by the tape, thus post-exposure observations of dust left on the sample after the sampling would evidence an improved adhesion as a result of the exposure.

3. Results and discussion

There were a total of three experiments performed, each including sample exposure in 1 to 3 similar D-fueled ELMy H-mode discharges. Each experiment was characterized with different fueling and heating rates which determined the local plasma conditions at the DiMES location. In the last experiment, the toroidal field direction was reversed. This only had a noticeable effect on the C dust which will be described below. All three experiments were conducted in the lower single null configuration with the OSP placed on or swept over DiMES. New samples were added to the DiMES head after each exposure leaving already exposed ones in place, see Table 1. E.g. Sample 2 has been exposed in all three experiments. Table 1 presents a summary of the three experiments. For convenience, they will be referred to respectively as **low**- **high**- and **medium**-power exposures. Exposure duration is the time during the current flat-top phase of the shot when the OSP was in the vicinity of the DiMES center. $P_{tot.}$ is the total power of applied heating; $q_\perp$ and $q_\perp^*$ are respectively inter- and intra-ELM deposited heat flux densities at the DiMES radius. They were either measured by the IR camera or calculated from the LP- and DTS-measured n_e and T_e data using the formula $q_\| = \gamma n_e c_s k T_e$, where $\gamma = 7$ is the sheath power transmission factor and c_s is the ion sound speed. Then $q_\perp = q_\| \sin(\alpha)$ with α being the B-field line angle to the target surface, typically 1.1°–2.5°. It was recently demonstrated in [10] that at least in L-mode lower power discharges there is a satisfactory agreement between the heat fluxes inferred from the IR camera, the Langmuir probes and DTS when $\gamma = 7$ is used. We also found a satisfactory agreement between the measurements performed with these diagnostics in H-mode discharges.

In ELMy plasmas the complication is that the diagnostics have to be running at high sampling rate to be able to resolve individual ELMs. DTS pulses have repetition rate 50 Hz and duration ~10 ns.

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