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Migration of artificially introduced micron-size carbon dust in the DIII-D divertor

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Abstract

Migration of pre-characterized carbon dust in a tokamak environment was studied by introduction of ~30 mg of micron-size (~6 μm median diameter) dust in the lower divertor of DIII-D using a DiMES sample holder. Direct exposure of the dust to high particle and heat fluxes in ELMing H-mode lower single-null discharges resulted in part of the dust being injected into the plasma. Following a brief exposure (~0.1 s) at the outer strike point, 1.5–2% of the total dust carbon content ($2–3 \times 10^{19}$ carbon atoms, equivalent to a few million dust particles) penetrated the core plasma, raising the core carbon density by a factor of 2–3. Individual dust particles were observed moving at velocities of 10–100 m/s, predominantly in the toroidal direction for deuteron flow to the outer divertor target, consistent with the ion drag force. The observed behavior of the dust is in qualitative agreement with modeling by the 3D DustT code.

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Keywords: Dust; DIII-D; DiMES; Carbon impurities; Visible imaging

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1. Introduction

The presence of dust in fusion plasmas has been long recognized and discussed in the literature (see Refs. [1–7] and references therein). While generally of no concern in the present day machines, dust may pose serious safety and operational concerns for the next generation of fusion devices such as the International Thermonuclear Experimental Reactor (ITER) [4]. Dust generation in next-step devices is expected to increase by several orders of

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magnitude due to the increased duty cycle and higher magnitude of particle and power fluxes deposited on the plasma facing components (PFCs) [4]. Dust accumulation inside the vacuum vessel may contribute to tritium inventory rise and can cause radiological and explosion hazards [4]. In addition, dust penetration of the core plasma can cause increased impurity concentration and degrade performance [5–7].

Dust particulates found in tokamaks and stellarators range in size between 10 nm and 100 μm [4,7]. The count-based median diameter as well as the diameter of the average mass of the tokamak dust is typically a few microns [4,7]. The chemical composition of dust is generally determined by the dominant PFC material. In tokamaks with vacuum chambers lined with carbon tiles ('all-carbon' machines), dust is mostly carbon. Dust in tokamaks is produced by intense plasma material interactions (PMI) during plasma operations as well as by entry activities during vents. Dust production mechanisms due to PMI include arcing, flaking of co-deposited layers, blistering, and brittle destruction [4,7]. Disruptions, 'carbon blooms' from leading edges, large edge localized modes (ELMs) and other transient events result in increased dust production [4,7]. Since the strongest PMI in a divertor tokamak usually occur at the divertor targets, dust production rates in the divertor region are expected to be higher than in the rest of the chamber. Theoretical estimates [5,6] and numerical modeling by the 3D Dust Transport (DustT) code [7] have shown that dust particles formed in the divertor can be accelerated by plasma flows to velocities of 10–100 m/s and escape from the divertor region, sometimes penetrating the core plasma. Below we provide experimental proof of long-range carbon dust migration in the DIII-D tokamak divertor.

Mobility of dust and its ability to penetrate the core plasma depend strongly on the dust size and chemical composition [5–7]. Validating dust migration models for a known dust material requires knowledge of the dust size and time-resolved trajectory. With 2D imaging techniques [2] dust trajectories can be recorded and velocities estimated, but there is usually no way to determine the dust size. Scattering techniques [3,8] can only resolve the size of very small particles and cannot determine velocities. Dust observation events are comparatively rare, on the average often less than one event per plasma discharge. The situation can be ameliorated by introducing dust of known composition and size into the divertor or scrape-off layer (SOL) and tracing its migration. Experiments with externally introduced dust have been previously performed in the JIPPT-IIU tokamak [3], where micron-size carbon dust was spread from the top of the vacuum chamber and detected by Thomson scattering. No noticeable effect on the plasma was observed for dust falls of up to 10^6 particles (10 μg) lasting for 20 ms. Here we report experiments where much larger amounts of micron-size carbon dust were placed in the DIII-D divertor and had a pronounced effect on the plasma discharge.

2. Experimental arrangement

DIII-D [9] is a large tokamak ($R = 1.67$ m, $a = 0.67$ m) with all-carbon (graphite) PFCs. DIII-D is equipped with the divertor material evaluation system (DiMES) [10] which allows inserting material samples into the lower divertor floor and exposing them to either a single plasma discharge or a series of reproducible discharges. In the experiments described here, a standard DiMES graphite head was used as a dust sample holder (Fig. 1). A shallow dimple with a smooth depth profile to avoid leading edges, 0.7 mm deep in the center and ~15 mm in diameter, was made in the plasma-facing (top) surface of the head. Pre-characterized graphite dust consisting of 0.5–10 μm diameter flakes (~6 μm median diameter from volume-count distribution) was placed in the dimple and the holder was inserted in the lower divertor floor so that its top surface was level with the floor tiles.

Three separate dust exposure experiments have been performed. All exposures were to high power ELMing H-mode discharges in lower single-null (LSN) magnetic configuration with the strike points swept across the divertor floor. The diagnostic arrangement is illustrated in Fig. 2. Three cameras with a view of the dust holder were available. A tangential view (shown by darker shading in Fig. 2) was split between two CID cameras ('tangential TVs') with rates of 60 fields/s and changeable filters. One of the cameras had an image intensifier and each field exposure could be gated down to 1 ms. Spatial resolution of both tangential TVs was about 1.5–2 cm. Another 60 fields/s CMOS camera ('DiMES TV') viewed the dust holder from the top (view cone shown by lighter shading in Fig. 2) with a spatial resolution of about 1.5 mm. One chord of the multi-chord divertor spectroscopy (MDS) system was centered on top of the dust holder (line of view

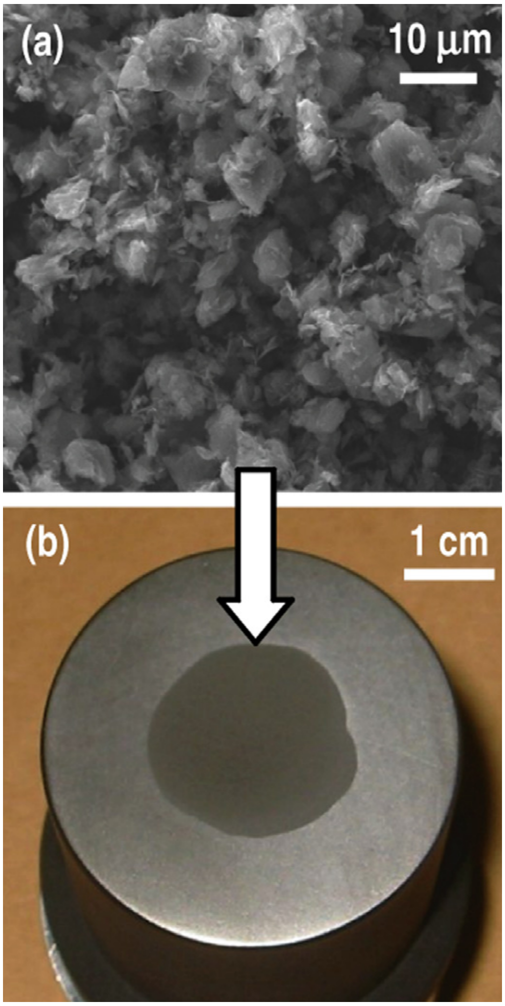

Fig. 1. Carbon dust used for experiments in DIII-D (a); dust holder filled with about 30 mg of dust (b).

shown in Fig. 2). A fiber optic telescope coupled to a photomultiplier with a CIII filter ('filterscope') was focused at a spot at the radial position of DiMES, displaced toroidally by about 40 cm. The XUV survey spectrometer (SPRED) monitored the core CIII radiation. The charge exchange recombination (CER) spectroscopy system was used to measure the core carbon density profiles.

3. Experimental results

For the first dust exposure in DIII-D, a small amount of loose dust (∼1 mg) was placed in the holder and exposed to a LSN H-mode plasma discharge with strike point sweeps (shot 117294). The outer strike point (OSP) was swept over the dust holder twice, moving first inwards then outwards. No noticeable effect on the discharge parameters was observed, and cameras equipped with CI and CII filters did not register any moving dust. The only indication of the dust presence came from MDS which showed step-like increases in both the CI line and continuum radiation by about a factor of three during the first OSP passage over the holder. CER was not available.

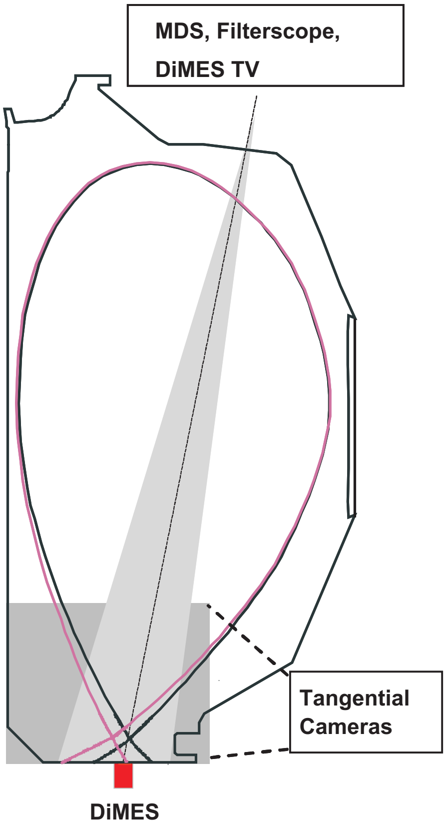

Fig. 2. Dust exposure geometry and diagnostic arrangement.

For the second experiment a larger amount of dust, about 25 (±2) mg, was used. In order to make sure that the dust was not blown away during pump-down and survived until the plasma exposure, a suspension of dust in ethanol was placed in the holder and allowed to dry. Upon drying, it formed a uniform layer clinging to the holder (Fig. 1(b)). The sample was exposed to a LSN H-mode discharge (shot 122428) with the following parameters: toroidal magnetic field, $B_T = 2$ T, plasma current, $I_p = 1.4$ MA, neutral beam heating power, $P_{NBI} = 5$ MW, average plasma density, $\bar{n}_e = 5 \times 10^{19}$ m^{-3}. The strike point sweep used is illustrated in Fig. 2, showing the separatrix positions at 1.5 s (OSP outboard of DiMES) and 2.0 s

(OSP on DiMES) into the shot. In order to better detect the dust, the DiMES TV and the gated tangential TV were equipped with near infrared filters (Kodak Wratten 89B) with less than 1% transmission below 680 nm. The non-gated ('standard') tangential TV was equipped with a CIII filter.

The first signs of the dust presence came during the startup when the DiMES TV registered a bright spot roughly the size of the dust layer on top of the holder. During the current ramp-up, the dust holder was kept in the private flux region and no dust injection was observed. Beginning at 1.72 s into the discharge, the strike points were swept radially inward (Fig. 3(b)). When the OSP reached the dust holder at about 2 s into the discharge, a massive dust injection occurred. The DiMES TV was saturated while the gated tangential TV observed dust trajectories directed towards the plasma core in the poloidal projection plane. The standard tangential TV observed CIII light striated along the magnetic field lines extended over the dust holder. Increase of the continuum radiation from MDS was more than a factor of 50. Both SPRED and the divertor filterscopes showed increase of CIII light (Fig. 3(c) and (d)). CER observed a strong increase in the core carbon density, peaking at 2.1 s at more than twice the pre-injection level (Fig. 4). Only a minor increase in the average plasma density was observed (Fig. 3(a)).

As the OSP was swept further inwards, the dust injection rate decreased and the carbon light intensity relaxed close to the pre-injection levels. However, dust injection continued at a reduced level and the DiMES TV registered individual dust trajectories, as illustrated in Fig. 5. No large-scale injection was observed on the second, outwardly directed, OSP pass over the holder. After the second OSP pass, dust injection ceased. The holder was kept inserted for the next plasma discharge with similar plasma parameters and strike point sweeps. Some dust injection was still observed by the DiMES TV but the amount of the injected dust was apparently too low to cause any effect on the core plasma. When the holder was removed from

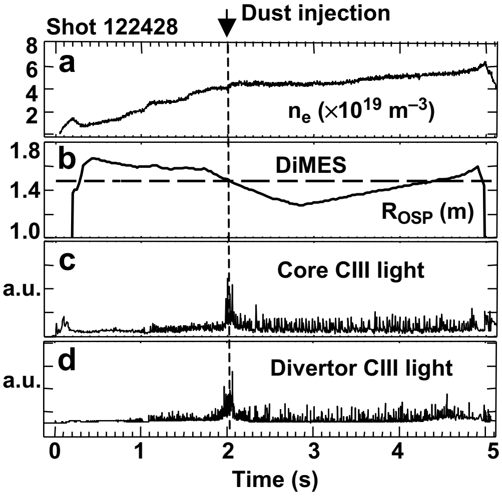

Fig. 3. Time traces of the average plasma density (a), radial position of the OSP (b), core (c) and divertor (d) CIII light intensity during a plasma discharge with dust injection. The radial position of DiMES is marked by the horizontal dashed line in (b).

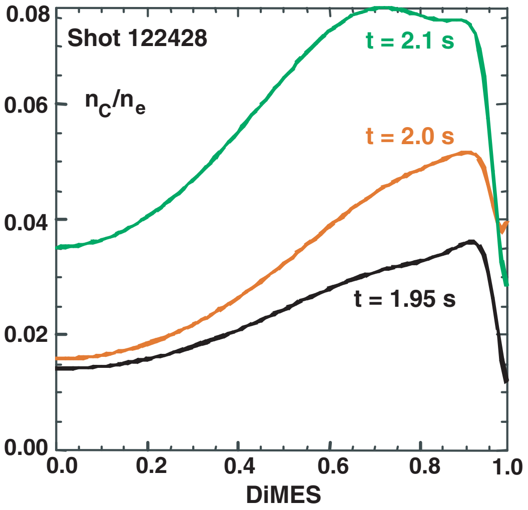

Fig. 4. Radial profiles (versus normalized minor radius) of the normalized carbon density immediately before, during and after the dust injection. The error bars for the measurements (not shown) are about ±20%.

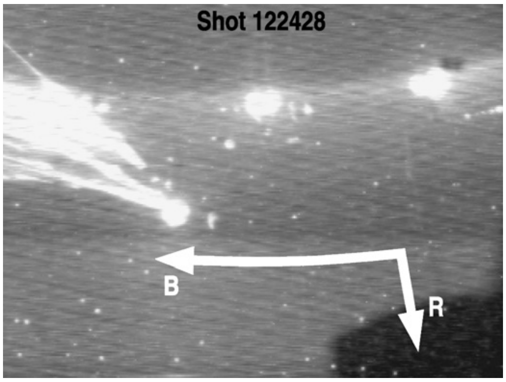

Fig. 5. Dust tracks recorded by DiMES TV with near IR filter. The bright spot where the tracks originate is the glowing dust remaining in the holder. Two other bright spots are the bolt holes between the floor tiles.

DIII-D, a small amount of dust was still remaining on the bottom of the dimple.

The third dust injection experiment (shot 123308) was performed in a way similar to the second, with ~35 (±3) mg of dust used. The discharge parameters were slightly different: $B_T = 2$ T, plasma current, $I_p = 1.5$ MA, neutral beam heating power, $P_{NBI} =$ 8 MW, average plasma density, $\bar{n}_e = 4 \times 10^{19}$ m^{-3}. Two major dust injection events were observed: first when the X-point was lowered to induce an L–H transition and landed on top of the dust holder, and second when the OSP was swept across the holder as in the previous experiments. Both injection events resulted in a core carbon density increase by a factor of 2–3. Unlike previous experiments, both injection events were followed by a notable increase in the average plasma density. The density increase by a factor of 2.5 after the L–H transition and the first dust injection event was probably mostly due to the improved confinement. The second dust injection event was most likely responsible for the following density increase of ~30%.

4. Discussion

Data collected in this series of experiments allows us to make estimates of the dust velocities and core penetration efficiencies, as well as speculate about the dominant forces influencing the dust motion. Only a lower-bound estimate of dust velocities can be done from the camera data by dividing the observed track lengths by the exposure time. The available images yield velocities in the range of 10–100 m/s.

Theoretical estimates [6] and numerical modeling by the DustT code [7] predict that the ion drag force is the dominant force acting on the dust particles in a tokamak divertor and that the dust motion is predominantly in the direction of the local ion flow, which in the divertor is mostly toroidal. Images recorded by the DiMES TV confirm this. Both theoretical [5,6] and numerical [7] studies predict that dust particles can bounce off the surface inhomogeneities and move towards the plasma core. Dust motion towards the core was indeed observed by the tangential TV.

The core penetration efficiency of the dust formed in the divertor is predicted by the DustT modeling to be in the range of a few percent. From the core carbon density increase following the dust injection events, as measured by CER, we can estimate the amount of carbon reaching the core. For the event illustrated in Figs. 3 and 4, the normalized carbon density increased by a factor of 2–3 throughout the shown radial range. For the average plasma density of 5×10^{19} m^{-3} and plasma volume of 20 m^3, this corresponds to $2 \pm 0.4 \times 10^{19}$ carbon atoms, or about 20 m^3. Therefore, during this event about 1.6 ± 0.3% of the total carbon content of the dust (equivalent to a few million dust particles) has reached the plasma core. During the two injection events of the third experiment, the amount of carbon reaching the core was slightly larger – about 2 ± 0.4% of the total dust content in each event. We should stress that this number may not be directly comparable to the dust penetration efficiency predicted by the DustT modeling. First, we cannot distinguish between the carbon transported to the core in the form of dust (and evaporated inside the core) and that from the dust vaporized in the boundary plasma and transported into the core by other processes such as diffusion and convection. Second, the modeling assumes that the dust particles have non-zero velocities to begin with (i.e., all the particles are mobile), while in our case there is some finite efficiency of the particle ejection from the holder into the plasma.

5. Summary and conclusion

We present direct experimental evidence showing that micron-size carbon dust contained in a tokamak divertor can become highly mobile and reach the core plasma. Whether the dust can be a serious contributor to the core impurity contamination in the present day or future tokamaks remains an open question. The answer would depend on factors such as dust production and transport rates that are at present poorly known. Rayleigh scattering measurements of dust in DIII-D during normal plasma operation [8] indicate that it is not a significant contributor to core contamination. Our results can serve to validate the models that can be used to predict dust transport in the next-step devices such as ITER.

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