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Abstract. Studies of submicron dust using Mie scattering from Nd:YAG lasers and video data of micron to sub-millimeter sized dust on DIII-D tokamak have provided the first data of dust sources and transport during tokamak discharges. During normal operation on DIII-D dust observation rates are low, a few events per discharge or less. The net carbon content of the dust corresponds to a carbon atom density a few orders of magnitude below the core impurity density. Statistical analysis of Mie data collected over months of operation reveal correlation of increased dust rate with increased heating power and impulsive wall loading due to edge localized modes (ELMs) and disruptions. Generation of significant amounts of dust by disruptions is confirmed by the camera data. However, dust production by disruptions alone is insufficient to account for estimated in-vessel dust inventory in DIII-D. After an extended entry vent, thousands of dust particles are observed by cameras in the first 2-3 plasma discharges. Individual particles moving at velocities up to ~300 m/s, breakup of larger particles into pieces, and collisions of particles with walls are observed. After ~70 discharges, dust levels are reduced to a few events per discharge. In order to calibrate diagnostics and benchmark modeling, milligram amounts of micron-sized carbon dust have been injected into DIII-D discharges, leading to the core carbon density increase by a factor of 2-3. Following injection, dust trajectories in the divertor are mostly in the toroidal direction, consistent with the ion drag force. Dust from the injection is observed in the outboard midplane by a fast framing camera. The observed trajectories and velocities of the dust particles are in qualitative agreement with modeling by the 3D DustT code.

Keywords: Dust; DIII-D; DiMES; Visible imaging; Mie scattering
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INTRODUCTION

Dust is commonly found in magnetic fusion devices (see [1-4] and references therein). While generally of no concern in the present day machines, dust may pose serious safety and operational concerns for the next step devices such as International Thermonuclear Experimental Reactor (ITER), where dust generation is expected to increase by a few orders of magnitude [2]. Dust accumulation inside the vacuum vessel can contribute to tritium inventory rise and cause radiological and explosion hazards [2], thus in-vessel dust inventory in ITER will be strictly regulated. In addition, dust penetrating the core plasma can cause increased impurity concentration and degrade performance [4].

Dust particulates found in tokamaks and other fusion devices range in size between 10 nm and 100 μm [1-4]. Chemical composition of the dust is determined by the plasma facing component (PFC) materials. Dust production mechanisms in tokamaks with carbon-based PFCs include flaking of redeposited layers, brittle destruction of graphite, arcing, agglomeration from supersaturated vapor, and growth from hydrocarbon molecules [3]. Disruptions, large Edge Localized Modes (ELMs) and other transient events result in increased dust production [2,4]. Dust studies on DIII-D tokamak are aimed at developing a detailed physics basis for improved predictive capabilities of dust generation and accumulation by identifying the dominant dust sources, obtaining estimates of the dust generation rates, and understanding the physics of the dust transport.

MEASUREMENTS OF NATURALLY OCCURRING DUST

DIII-D [5] is a tokamak with major and minor radii of 1.67 m and 0.67 m, and all-carbon (graphite) PFCs. It has two poloidal divertors and can be operated in lower single null (LSN), upper single null (USN), double null (DN) and wall-limited magnetic configurations. The machine is outfitted with advanced plasma diagnostics including a Thomson scattering system based on 8 ND:YAG lasers and used primarily for the measurements of the electron density and temperature profiles. Spectrally non-shifted detector channels allow for detection of dust particles via Mie scattering [6,7]. The diagnostic can resolve the size of small particles between 50–250 nm in diameter. The observation rates are low, a few events per discharge or less. Nevertheless, statistical analysis of the data provides an estimate of the total dust content in the edge and scrape-off layer (SOL) plasmas and allows establishing trends in the dust production rates. It has been shown that during normal plasma operations in DIII-D dust is not a major impurity source, with total carbon content of the dust being less than a few percent of the plasma carbon impurity content [6]. Statistical evidence points to increased dust production in discharges with edge localized modes (ELMs) and disruptions. Size distribution of the dust particles is best approximated by a log-normal distribution [Fig. 1(a)]. The dust density is barely above the detection limit at the separatrrix and increases with distance into the SOL [Fig. 1(b)].

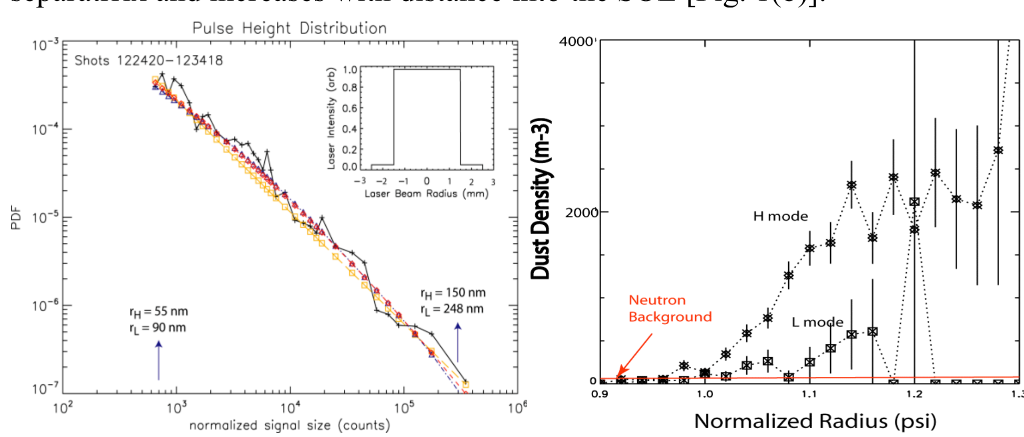

FIGURE 1. Dust size distribution (a) and radial density profile (b) measured by Mie scattering.

Another technique suitable for dust measurements is optical 2D imaging by cameras. A few standard frame rate CMOS and CID cameras are available including two cameras viewing tangentially into the lower divertor and one camera looking vertically down at the divertor floor. These cameras can resolve only the largest dust particles (tens of microns in size). A fast framing CMOS camera (up to 26000 frames/s at 256x256 pixel resolution) viewing the outboard SOL can resolve particles down to ~4 μm in diameter. During "normal operations", i.e. when the vacuum vessel walls are well conditioned and there are no major disruptions, dust observation rates are low. Disruptions often generate significant amounts of dust which is directly observed by the fast-framing camera. An image of dust produced by a disruption is shown in Fig. 1(a). A single disruption produces up to ~10000 dust particles, corresponding to between 0.01–1 mg of carbon, depending on the dust size which is hard to determine from the camera data. Taking the upper bound estimate, disruptions in DIII-D may produce up to ~1 g of dust over a 15 week experimental campaign. This is two orders of magnitude below the estimated dust inventory in DIII-D as measured by collection techniques during entry vents [1], so other mechanisms are likely to dominate the dust production. It is possible that a large part of the dust inventory in DIII-D is created by in-vessel activities during vents. In the first 2-3 plasma discharges after an entry vent, cameras detect thousands of dust particles in each discharge. Individual particles moving at velocities of up to a few hundred m/s and breakup of larger particles into pieces are observed. An example of dust tracks observed by a standard rate CMOS camera viewing the lower divertor from above is shown in Fig. 2(b). After about 15 discharges dust is virtually gone during the stationary portion of a discharge, and appears at much reduced levels during the plasma initiation and termination phases. After a few days of plasma operations (about 70 discharges) dust levels are further reduced to just a few observed events per discharge.

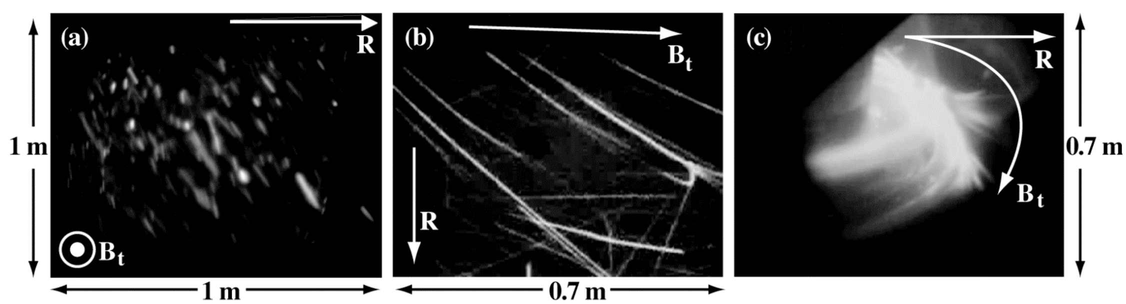

FIGURE 2. Dust in DIII-D: (a) dust produced by a disruption (fast camera, tangential view of outboard SOL); (b) dust observed after an entry vent (standard rate camera, looking down in the lower divertor); (c) intentional dust injection into the lower divertor (standard rate camera, tangential view of the lower divertor).

MEASUREMENTS OF INTENTIONALLY INTRODUCED DUST

2D imaging allows to record particle trajectories and estimate velocities, but determination of the particle size, chemical composition and origin is hardly possible. Injections of pre-characterized dust from a known location can be used to calibrate diagnostic measurements and benchmark modeling of the dust dynamics and transport.

Migration of carbon dust was studied in DIII-D by introduction of micron-size (~6 μm median diameter) graphite dust in the lower divertor [8]. A sample holder filled with ~30 mg of dust was exposed to high-power LSN ELMing H-mode discharges with strike points swept across the divertor floor. Following a brief exposure (~0.1 s) at the outer strike point, part of the dust was injected into the plasma [Fig 2(c)]. About 1.5%-2% of the total dust carbon content ($2\text{-}3\times10^{19}$ carbon atoms, equivalent to a few million dust particles) penetrated the core plasma, raising the core carbon density by a factor of 2–3 and resulting in a twofold increase of the total radiated power. 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 velocities and trajectories of the dust particles are in qualitative agreement with modeling by the DustT code [4,9], which solves equations of motion for dust particles in 3D self-consistently using a plasma background from the UEDGE code. The fast framing camera observed large amounts of injected dust in the outboard SOL, thus confirming DustT prediction that dust can migrate from the lower divertor into the main chamber [9]. An injection of diamond dust of finely calibrated size between 2-4 microns was recently performed. Dust from injection was observed by the fast camera, but requited digital background subtraction to be resolved. Therefore, it was experimentally demonstrated that 4 micron dust is about the smallest that can be resolved by the fast camera in the existing setup at DIII-D.

SUMMARY AND ACKNOWLEDGMENTS

In summary, progress has been made in characterization of naturally occurring and artificially introduced carbon dust in DIII-D. Micron size dust has been shown to be highly mobile, travelling at velocities of up to hundreds of m/s. Dust does not present operational concerns in DIII-D except immediately after entry vents. Disruptions produce notable amounts of dust, but dust production by disruptions alone is insufficient to account for the estimated in-vessel dust inventory in DIII-D. ELMs are also observed to produce dust in DIII-D. These impulsive sources of dust remain a concern for ITER, where wall loads from ELMs and disruptions will be very large compared to those on DIII-D.

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