Correlations of Dust Particles With Plasma Parameters in DIII-D

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Abstract. The first quantitative measurements of dust size and spatially localized number density during plasma discharges have been made in DIII-D. The particles are observed by Rayleigh/Mie scattering of ND:YAG lasers during plasma operations. The particles observed during discharges are significantly smaller (80 nm mean radius) than those injected for trajectory studies, observed by cameras and collected with wipes of the tiles after run campaigns. The small volume (0.2 cm^3) of each observation location and short laser pulse length provide a good localization of the dust in the tokamak. Dust produced in the vessel is comprised primarily of carbon from the plasma facing components. The observed dust particles do not penetrate into the plasma core and event rates inside the plasma edge are consistent with the neutron background rate. A typical shot has 0.7 observed particles in the scrape-off layer (SOL), producing a sample set of 2500 dust particles from the 3630 discharges in the DIII-D 2004/2005 run campaign which corresponds to a mean number density of 4000 m^{-3} in the SOL, which corresponds to a carbon atom density 5 orders of magnitude lower than the core carbon density. Studies of these particles show significant asymmetries in the dust densities for different plasma configurations. There is a significant increase in dust density with H-mode discharges relative to L-mode discharges. The dust density in H-mode discharges is sensitive to many parameters including the pedestal temperature and inner wall gap.

1. Introduction

Dust consisting of small loose particles ranging in size from tens of nanometers to millimeters has been observed in many plasma fusion devices. A recent review of dust in tokamaks outlines the operational and safety issues of dust and previous experimental results measuring dust density and particle size [1]. The large heat fluxes, long discharges and high divertor particle fluxes in next step machines will make plasma wall interaction (PWI) control critical for success. A better understanding of PWIs is necessary to understand the thinning of plasma facing components (PFC) by erosion, control contamination in the plasma core, and manage the accumulation of tritium in the vessel walls and loose dust. Rayleigh/Mie scattering measurements made concurrently with electron density and temperature measurements of the DIII-D Thomson scattering system can detect dust particles as small as 50 nm. Combining data from a large number of shots provides information on the dependence of dust density on plasma parameters. Many processes including sputtering and sublimation can produce erosion from the PFCs [2] and inject dust into the tokamak; studies at DIII-D indicate that the majority of neutral carbon originates from the divertor region [3]. Dust particles are observed moving quickly following the field line in plasma discharges [4] which indicates that the dust particles become charged and can travel long distances in the scrap off layer (SOL). Dust particles collected after vents to air at DIII-D are mostly comprised of carbon from the PFCs and are typically 1 μm in diameter [5].

Recent analysis of the scattered light signals from dust particles indicate an average radius of 80nm for the dust particles in the DIII-D SOL [6]. Time-averaged dust concentrations as high as 6000 m^{-3} are observed far into the SOL and drop to near zero at the last closed flux surface during periods with plasma currents above 900 kA. The average dust density of 4000 m^{-3} represents a carbon atom density of 10^{13} m^{-3} in the SOL which is too small to be the source of the carbon ion density in the core plasma of >10^{18} m^{-3}. The dust density is significantly higher during H-mode shots than it is during L-mode shots and correlations with plasma parameters suggest that edge localized modes (ELMs) are a significant source of the observed dust.

2. Dust Measurements With the Thomson System

The DIII-D Thomson system measures electron density and temperature in the core and divertor of the plasma [7,8]. Polychromators measure the scattered light spectrum over a series of adjacent wavelength bins for each 0.2 cm^{-3} viewing location (Fig. 1). An additional narrow bandpass filter at the laser wavelength is used for Rayleigh scattering calibrations of the detectors absolute sensitivity. This filter is not used in the analysis of the Thomson scattering but is very sensitive to Rayleigh or Mie scattering from dust particles in the vessel. Four 20 Hz lasers are used to measure the dust density in the SOL and an additional laser passes through the lower divertor. The divertor measurements have a higher dust density but lower statistics due to the lower sampling rate from having one laser instead of four and many shots cannot be analyzed for dust due to high levels of stray, scattered laser light.

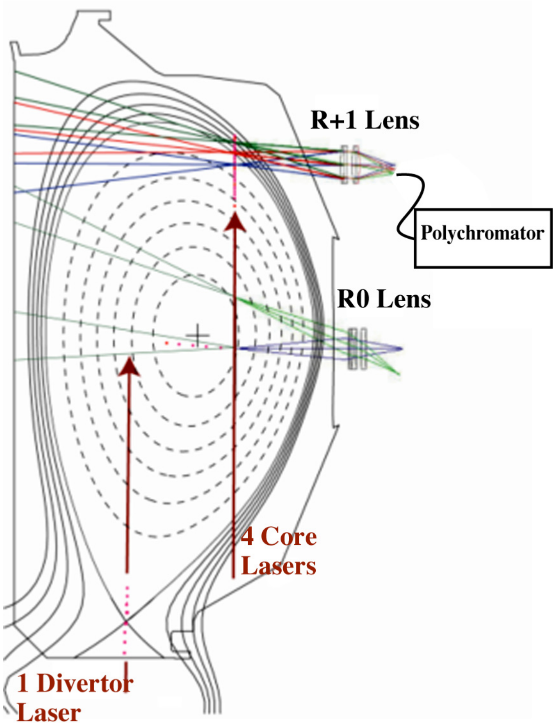

FIG. 1. Locations of the Thomson measurement locations. Detail of the SOL.

A small residual event rate is observed inside the last closed flux surface. An additional detector was added to the Thomson system to monitor noise sources for the dust measurements. This detector does not see any light from the vessel but is sensitive to neutrons and electronic noise sources. The detection rate in the background detector is consistent with the rate of events seen in the channels away from the laser line and the laser channels in the plasma core. A background proportional to the signal from neutron detectors on the machine accounts for the observed signals inside the plasma core. The neutrons contribute an average false detection rate equivalent to 11±1 m^{-3} which is significantly lower than the observed density in the SOL.

Dust particles are observed in the scattered light signals during plasma discharges. The scattering volumes for the system are small, the laser repetition rate is low, and the dust density low so particles are observed infrequently. A sample set total of 2500 SOL dust particles in 3630 discharges were observed during the 2004/2005 run campaign which corresponds to a mean number density of 4000 m^{-3} during the shot after the current ramp. The statistical analysis of this large group of shots can provide experimental evidence of parameters which affect the dust density during DIII-D discharges.

The data from the 2004-2005 DIII-D run campaigns include a significant number of different running conditions. Upper single-null (USN) H-mode and lower single-null (LSN) L-mode plasmas are the most common. Dust is observed in all types of plasma discharges but H-mode plasmas have a significantly higher dust density than L-mode plasmas (Fig. 2). A recent discovery at the DIII-D facility is the existence of an operation mode known as quiescent H (QH) mode [9]. These reverse plasma current shots have high confinement and D_α emission in the edge but no ELMs. Comparisons of the QH and ELMy H-mode data show significantly lower dust levels in the QH mode discharges. There is insufficient QH mode data to determine the dust density profiles accurately but spatial averaging gives slightly larger densities than L-mode. This is consistent with models of dust production which suggest ELMs can cause significant erosion of the divertor and walls [10].

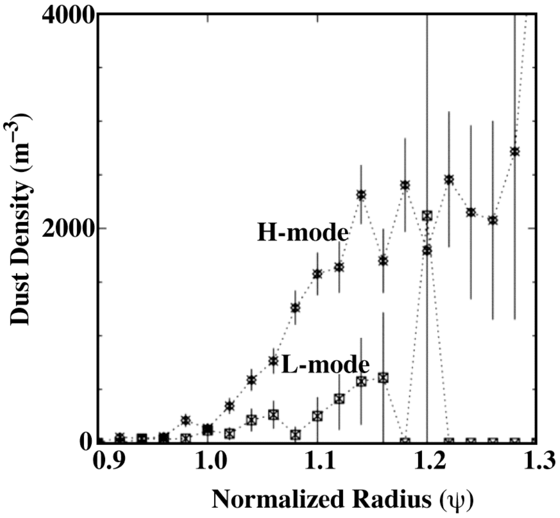

FIG. 2. Dust density rises from the last close flux surface into the SOL.

3. Dust Rate Correlations

Dust has been observed with this system during calibrations with argon gas after entries in the vessel but not during maintenance periods without venting. Injecting one torr of argon gas can disturb significant amounts of dust after a vessel entry. After operation periods with no vessel entry, dust is not observed with up to 4 torr of argon gas added to vessel. Near the end of the 2004-2005 run campaign, data from the lasers during the initial gas puff before breakdown was acquired to look at dust levels before the beginning of shots. Very little dust is observed at the start of plasma discharges. Initial gas injection starts at -300 ms and breakdown at -50 ms. The dust density observed before breakdown is 100 m^{-3} (Fig. 3). This suggests that very little loose dust is disturbed by injected gas during normal plasma operations in DIII-D. The low carbon atomic density in the vessel of $1x10^{11}$ m^{-3} during the breakdown phase has no effect on the breakdown.

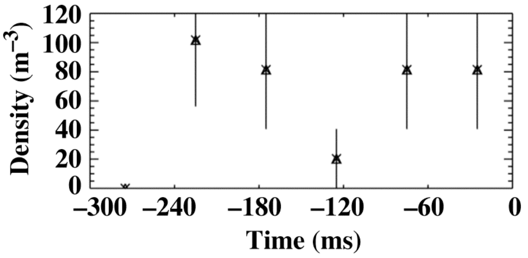

FIG. 3. Low levels of dust are observed between shots after prefill with gas.

3.1. Effect of Pedestal Conditions

Steady-state H-mode plasmas have good edge confinement with sharp temperature and density gradients. This edge confinement makes H-mode of great promise for future plasma devices and ITER [11]. H-mode plasmas can drive a number of instabilities including ELMs which relieve the edge pressure gradient. ELMs are characterized by a fast drop in the edge density and temperature inside the separatrix and have a complex structure with torrodial mode numbers of 10-15 [12]. They can cause significant localized heating on short time scales on the divertor and wall PFCs when they relax [13]. This localized energy deposition can cause severe erosion and dust production. ELMy H-mode plasmas represent most of the sample of dust particles because the majority of shots during the 2004-2005 campaign were ELMy H-mode and the dust density is higher in these shots. This suggests dust is a more significant problem for H-mode discharges and studies of the dependence of dust rate on plasma parameters are focused on H-mode shots.

Energy transfer during ELMs has a complicated dependence on the pedestal characteristics with a reduction in fractional energy transfer for high n/n_G [14]. The fraction of stored pedestal power lost in ELMs drops for high density discharges. Comparisons of the dust density with the average electron temperature and density pedestal heights show strong dependence of the dust density in the SOL with the electron pedestal temperature (Fig. 4). High pedestal temperatures are also correlated with higher injected powers and stored energy in the pedestal. Previous studies have shown that the ELM energy loss increases strongly as the pedestal density decreases; hence, it is not surprising that higher pedestal temperatures correlate with more dust in the SOL.

High core density shots which are associated with greater stored energy in the pedestal and lower pedestal temperatures have a lower dust density (Fig. 5). The plasma density is not as strongly correlated with injected power as the pedestal temperature which suggests injected power does not strongly control dust density levels. The stored pedestal energy is flat above a density of $2.5\text{x}10^{19}$ m^{-3}but ELMs at these high densities carry a lower fraction of the pedestal energy. This dependence combined with the pedestal temperature results are strongly suggestive of a significant role of ELM power in the dust levels at DIII-D.

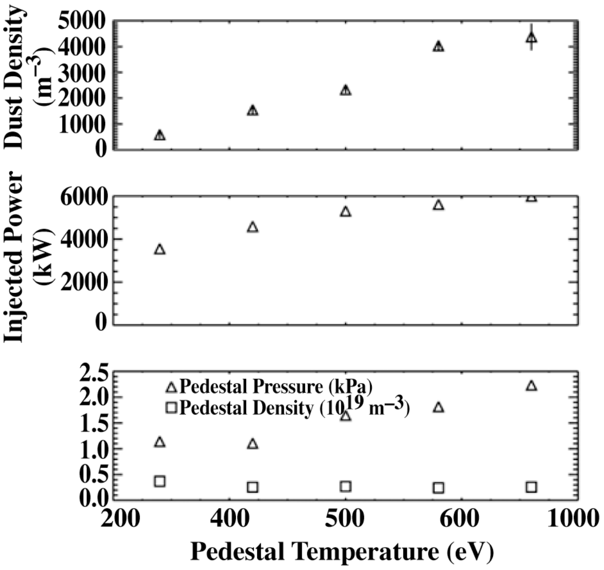

FIG. 4. Dust density increases with higher edge pedestal temperatures.

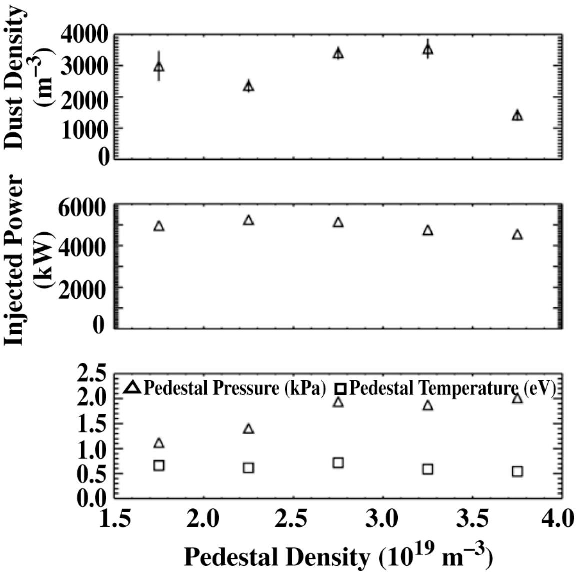

FIG. 5. Very high density pedestals are correlated with low dust densities.

3.2. Effect of Wall Gaps

SOL plasma parameters have a strong dependence on density and confinement regime. Studies [15] have indicated that H-mode plasmas can have significant plasma-wall iteraction. Studies of the dust data indicate that the inner wall gap is much more significant than the outer wall gap at DIII-D. The dust production for shots with a small separation between the inner wall and the last closed flux surface is larger than for larger gaps (Fig. 6). The gap between the outer wall and the last closed flux surface is not as important (Fig. 7). The dust density is also very sensitive to the gap between the last closed flux surface and the plenum of the upper divertor (Fig. 8).

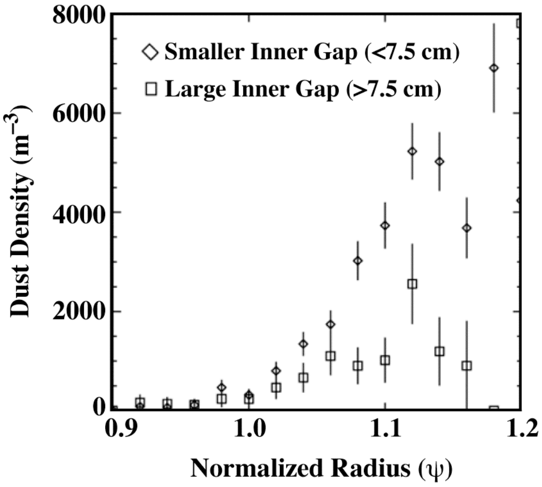

FIG. 6. Shots with small gaps between the inner wall and last closed flux surface have much higher dust densities than shots with large gaps.

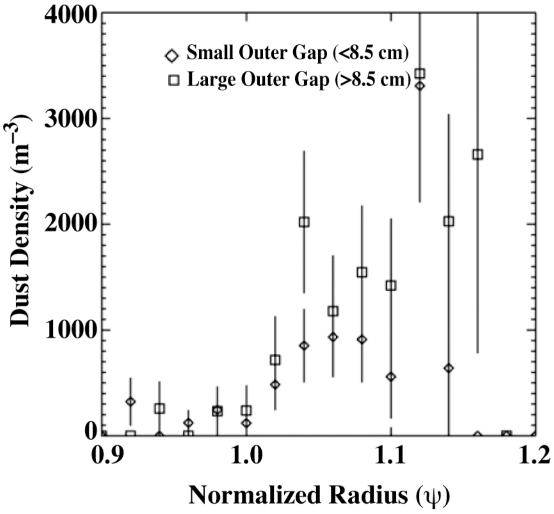

FIG. 7. Dust density is not sensitive to the outer wall gap when the inner wall gap is large.

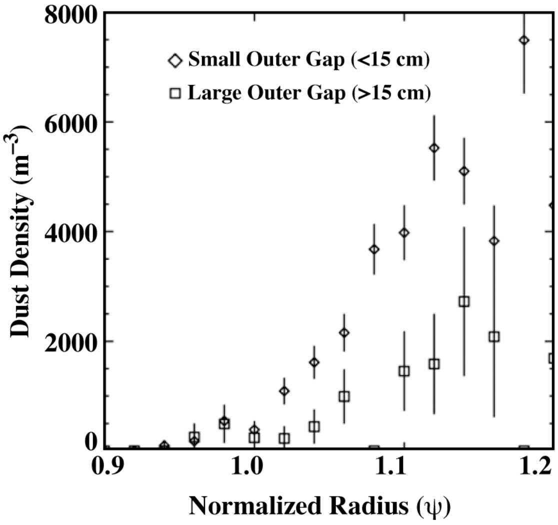

FIG. 8. Dust density increases for shots with small upper gaps.

The discharges with small inner gaps are observed to have significantly higher thermal radiation from the inner wall by background light monitors for the Thomson system. This higher inner wall temperature may contribute to higher erosion from ELMs. The upper plenum is close to the SOL measurement locations so increased interactions with this region would be expected to increase the dust density at least locally.

4. Time Evolution of the DIII-D Dust Density

The dust density at the start of shots is low. In L-mode, H-mode, and QH-mode the dust density is observed to increase during the first two seconds of the discharge (Fig. 9). The QH-mode discharges have much lower dust levels than the H-mode discharges although they have similar pedestal pressures. The QH-mode plasmas have higher pedestal temperatures and lower densities than typical H-mode discharges [16]. High temperature, low-density H-mode pedestals are associated with high dust levels in ELMing discharges but the dust levels in QH plasmas are relatively low.

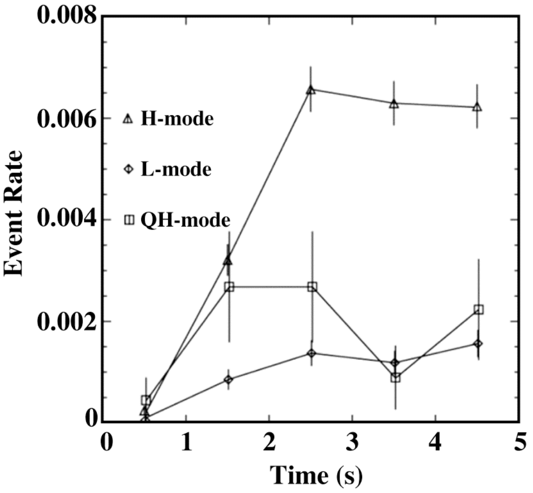

FIG. 9. Event rates increase during the first few seconds for all plasma categories. ELMing H-mode discharges increase to a significantly higher dust level.

The QH mode shots typically contain ELMing and quiescent phases with elevated D_α light but no ELMs. During the first two seconds of the discharge as the plasma density increases, QH and H mode plasmas have similar increases in dust density. During the quiescent phase the dust densities drop to levels similar to L-mode plasmas and dust is much more prevalent in ELMing phases of QH discharges. During the 210 QH mode shots contained in the dust database, dust was 5 times more likely to occur during ELMing phases of the shots than during the QH mode phases. The injected power and stored pedestal energies are similar in the H and QH discharges suggesting that ELMs play a very significant role in the dust density.

5. Conclusions

The DIII-D Thomson system directly measures the dust concentration in the SOL during plasma discharges. There is little dust before plasma breakdown, during the gas fill phase, and the dust density increases during the initial phase of plasma discharges. The 2004-2005 data contains three configurations with significant numbers of shots. Upper null biased H-mode discharges, lower null biased L-mode discharges, and reverse plasma current, QH mode discharges. The majority of the shots are H-mode and H-mode discharges are significantly more likely to contain dust events. There are not enough dust events in L-mode or QH mode shots to compare their density to plasma parameters.

ELMy discharges have significantly higher dust densities than similar performance QH discharges and both these configurations have higher dust densities than L-mode discharges. Statistical analysis of the data shows dust generation to be sensitive to pedestal temperature and the distance between the inner wall and the plasma. Higher pedestal temperatures are correlated with higher injected power and lower collisionality. The dust density is insensitive to the pedestal density except for very large densities which have lower dust densities. The data is consistent with ELMs playing the dominant role in dust generation. The dust density increases for high temperature, low collisionality pedestals which eject a larger fraction of stored pedestal energy per ELM. QH plasmas with high temperature, low collisionality pedestals have significantly smaller dust densities in the SOL.

Measurements of dust density during plasma discharges are necessary to test PFC erosion and transport models and understand plasma wall interactions. Understanding and controlling these interactions and dust levels will be critical for safe operation of ITER. This data provides quantitative measurements of the dust density during plasma operation in DIII-D and parameters which influence the dust density.

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