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CORRELATION OF THE PRESENCE OF SUBMICRON DUST OBSERVED IN DIII–D DURING NORMAL PLASMA OPERATION WITH PLASMA OPERATING PARAMETERS

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ABSTRACT

A database of dust events observed using the Thomson scattering systems on DIII-D has recently been expanded to incorporate over 2500 discharges over a 9-month period from the 2004-2005 campaign. The system is sensitive to dust particles of radius $\gtrsim$50 nm. Over this period of time, 5130 dust events were observed in the upper SOL region of the plasma and 4159 events in the lower divertor region. In the observation channels nearest the wall, the dust density is observed to be about 1.2×10^4 m^{-3} in the upper region and about 6×10^4 m^{-3} in the lower divertor. In both regions, the density drops sharply approaching zero at the last closed flux surface. Dust observation rate increases with increasing injected beam power in both regions. In the upper region, the observation rate increases sharply for a brief period after switching from operation with a dominant lower null to a dominant upper null. For a few shots after major disruptions, the observation rate increases slightly in the lower divertor but decreases slightly in the upper SOL.

1. INTRODUCTION

Dust seems to be omnipresent in the universe, from the kitchen to the depths of the cosmos, so it is not surprising that we find it in the tokamak as well. There are many possible sources of dust in a present day fusion device, including the formation of dust from many processes occurring at plasma facing surfaces during off normal plasma disturbances and during normal operation. Reviews of dust in tokamaks [1] and of the implication of plasma surface interactions for next-step fusion devices [2] have presented discussions on the operational and safety issues presented by dust and past experimental work. To date, most studies of dust in tokamaks have been limited to the collection of particulates that are accumulated over long times in the protected regions of the vessel [3], such as under pumping baffles and behind protective tiles, or images of particles large enough to be seen by video techniques [4]. In this paper, we discuss the correlation of submicron dust observation in the SOL and divertor region of DIII-D during normal plasma operation with plasma operational parameters.

Previously we reported on the measurement of the density and size distribution of dust in the scrape off layer (SOL) region during normal plasma operation on DIII-D using Rayleigh scattered light from a pulsed Nd:YAG laser beam [5]. The detection technique is sensitive to single dust particles with a radius as small as 50 nm. Narihara et al. [6] have discussed the observation of dust during plasma operations on JIPPT-IIU using Rayleigh/Mie scattering, however little analysis was possible due to the small amount of available data. Following the realization that dust was observable in the Rayleigh channels on DIII-D, automated routines were written to search the data and record events into a database. From the initial database based on a 3-month period of operation, an average density of dust in the upper SOL region of DIII-D near the plasma facing wall of 1.5×10^{4} m^{-3} was reported during operation with an active upper null (UN). The dust density was observed to drop quickly approaching the last closed flux surface, falling below the detection limit in the confined plasma region. Through modeling of the observed pulse height distribution, an average dust radius of 80 to 90 nm was found with a distribution width of ~40 nm. In the previous paper, arguments are presented that dust is unlikely to be a significant contributor to core carbon contamination. In this paper, data from a 9-month period of operation on DIII-D is presented. Over this period, sufficient data is accumulated to allow correlations regarding the observation of dust with plasma operational parameters.

2. ANALYSIS

The use of the Rayleigh scattering channel of the Thomson scattering diagnostic system on DIII-D for the detection of dust has been presented recently [5]. A schematic of the upper SOL and lower divertor Thomson systems [7,8] on DIII-D is shown in Fig. 1. A single dust particle in the viewing volume of the optical detection system viewing the Nd:YAG laser produces a large excursion in the wavelength channel centered at the laser wavelength (Rayleigh channel), as shown in Fig. 2. To investigate the dependence of dust observation on plasma operating parameters, the database of dust events has been expanded significantly to cover an operating period of 9 months, and the data from the lower divertor Thomson system was incorporated. For the upper SOL (lower divertor) a total of 2815 (2601) discharges were searched, for a total time of 9.9×10^3 s (9.1×10^3 s). During this time, a total of 7.9×10^5 (1.8×10^5) laser pulses were searched. Shot data from the DIII-D archive at the time each dust event is also accumulated. These data include plasma current, line averaged density, injected beam power, magnetic balance (dr_{sep}), and the amplitude of magnetic fluctuations observed at the wall. In some cases, the archived data from all laser times is also retrieved and stored.

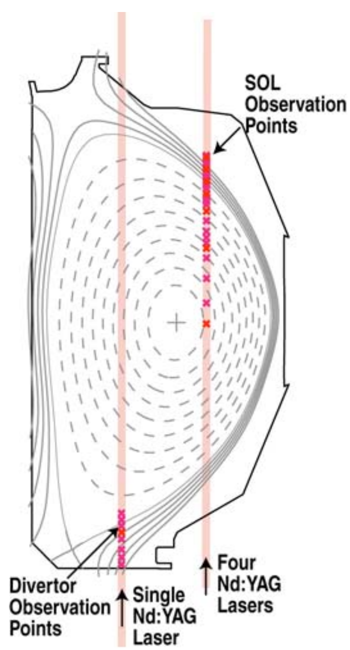

Fig. 1. The DIII-D Thomson laser paths and viewing volumes for the upper SOL and lower divertor are shown along with a flux surface plot of a lower single-null plasma. There are four collinear lasers passing along the path through the upper SOL, only one passes through the divertor.

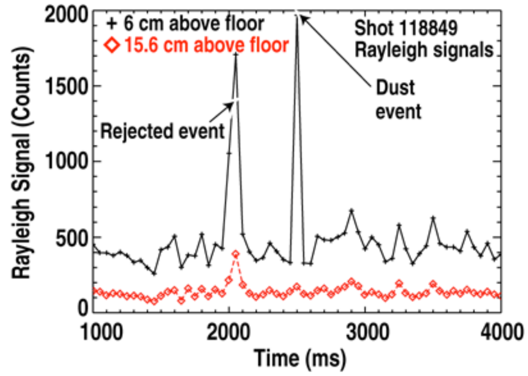

Fig. 2. The Rayleigh channel signal as a function of time is shown for two spatial channels for the plasma shown in Fig. 1. The event at 2500 ms is recorded as a dust event, but the event just after 2000 ms is rejected because it was observed in several spatial channels simultaneously.

Histograms of the number of dust events per laser pulse observed in each shot is presented in Fig. 3. In the upper SOL, there is a clear tendency for dust to appear when the UN is dominant, yet no such tendency is present in the lower divertor. The density of dust as a function of height (distance along the laser beams) is shown in Fig. 4(a) the upper SOL and Fig. 4(b) the lower divertor. In Fig. 4(a) it is again apparent that over this 9-month period of observation, dust is five times more likely to appear in the upper SOL region when the plasma configuration is UN dominant. From the histogram in Fig. 3(b), there is no significant dependence of the density of dust on the magnetic balance in the lower divertor. Comparing Figs. 4(a) and (b), it is clear that dust is much more prevalent, by a factor of five, in the divertor than in the upper SOL. In both the upper SOL and lower divertor, the dust density drops sharply going from the wall to the region of the confined plasma.

The tendency for dust to be more prevalent as the auxiliary beam heating power increases is illustrated in both Fig. 5(a) the upper SOL and Fig. 5(b) the divertor. In this figure, histograms of the occurrence of injected power at the time of dust events, binned over 2 MW, normalized to the occurrence rate over all times searched are shown for the lower divertor (plusses) and the upper SOL (diamonds). High beam power is much more often found associated with dust than over all times. The dependence on beam power is stronger in the lower divertor region than in the upper SOL. Examination of dust appearance with plasma current and line-averaged plasma density revealed little or no dependence.

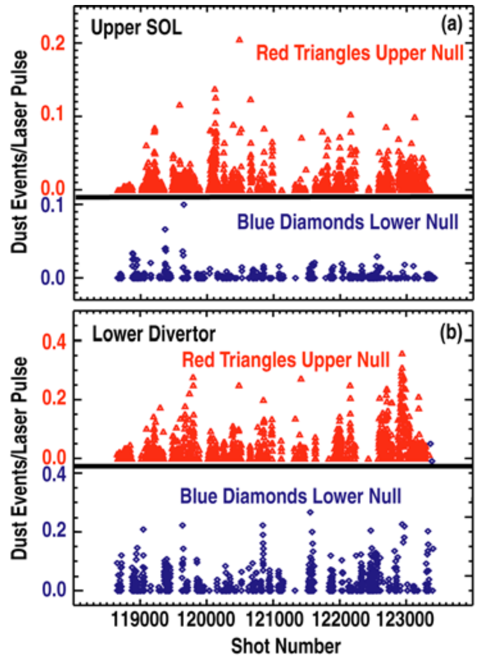

Fig. 3. Histograms of the number of dust events per laser pulse for all spatial channels as a function of shot number in the (a) upper SOL region, and (b) lower divertor region over the span of 9 months of operation on DIII-D. The upper curves in red are for UN dominant shots, the lower curves in blue are for LN dominance.

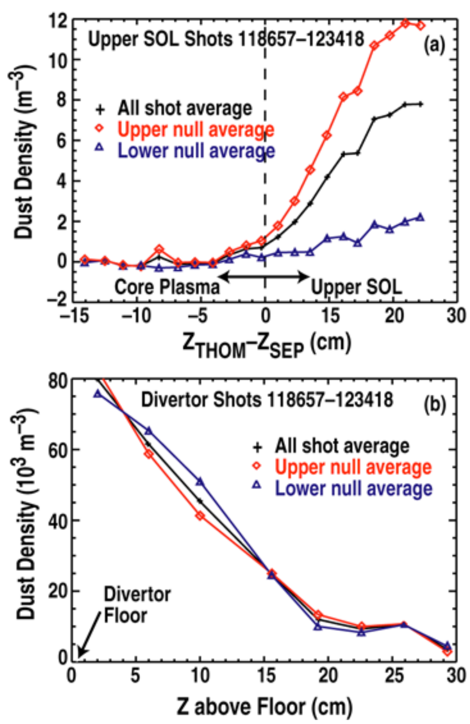

Fig. 4. The density of dust particles as a function of distance along the laser path for (a) the upper SOL (density is referenced to the average location of the separatrix over all times searched) and (b) the lower divertor (distance is referenced to the divertor strike plate).

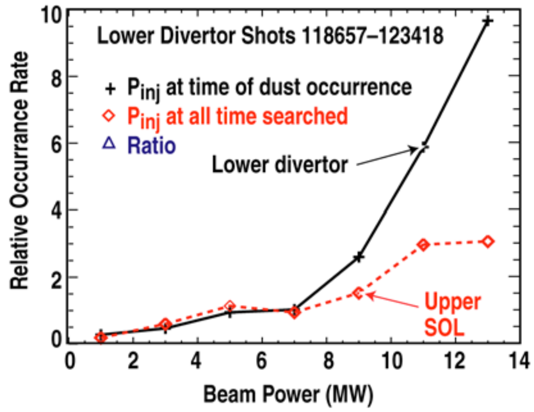

Fig. 5. Histrograms of the occurrence rates for inject power at the time of a dust event, binned over 2 MW, normalized the occurrence rate over all times searched for the lower divertor (plusses) and the upper SOL (diamonds).

A close examination of the dust occurrence versus shot for the upper SOL region [Fig. 3(a)] suggests that shots with unusually high dust occurrence rates appear after a long duration of operation in lower null (LN) dominance. A routine search found that over the 9-month period, there were 8 times when a switch to UN configuration occurred after at least 20 discharges were operated in LN. In Fig. 6 the number of dust occurrences per shot as a function of shot number following these eight switches is plotted, with an additional condition that at least 4 MW of beam power was injected into the plasma. It is apparent that dust rates rise and fall sharply in the upper SOL after a switch from LN to UN.

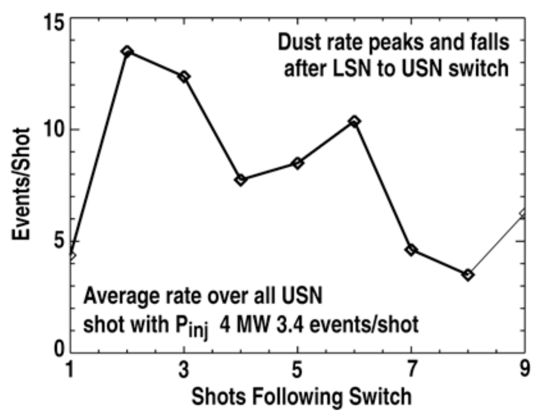

Fig. 6. The number of dust events per shot as a function of the number of shots following a switch from a period of LN dominant operation to a period of UN dominance, averaged over the 8 switches that occurred during the 9 months of data accumulation.

Disruptions are expected to be a source of dust, since the impulsive loading on the wall is very high. After disruptions, all Rayleigh channels of the DIII-D Thomson system show very large signals for many laser pulses, up to ~100 ms following the current quench. At the present time, we believe the most likely explanation is the induced mechanical vibration of the vessel, especially the laser entry and exit ports, causing the laser light to be scattered around the vessel and eventually into the Thomson detection system. The scattered light from the ports likely overwhelms signals from dust following disruptions. To check for any effect of disruptions on the production of dust during normal operation, a search routine was devised to find shots which disrupted, losing at least 800 kJ of energy to the wall. In the divertor region, for three shots following these disruptions the average dust occurrence rate was 2.1/shot (±0.07), whereas averaged overall shots the occurrence rate was 1.6/shot (±0.02). The errors quoted are purely statistical. It appears that disruptions cause a weak but noticeable increase in the rate of dust appearance in the divertor. In the upper SOL, the reverse is true. The occurrence rate averaged over three shots following a disruption is 1.4/shot (±0.06) while the average overall shots searched is 1.8/shot (±0.03). These data suggest that dust is removed from the wall by thermo-mechanical forces or by vibration from a disruption, then settles to the floor, decreasing subsequent observation in the upper SOL but increasing the rate in the lower divertor.

3. DISCUSSION

Submicron dust is observed in DIII-D on a routine basis using the DIII-D Thomson scattering system. The DIII-D plasma facing surface is >95% graphite tiles, mechanically attached to the inconel vessel and kept in good thermal contact with the vessel using a compliant layer of grafoil. In some areas, thin over-coatings of C:D redeposition films have built up on the plasma facing surface over a few years of operation, and in other areas, thin films of predominantly boron have built up from multiple plasma vapor depositions using diborane. As a result dust has multiple possible origins, including (1) dust left in the vessel from in-vessel maintenance during entry vents, (2) mechanical degradation of grafoil compliant layers under the plasma facing tiles, (3) direct ablation and volumetric condensation in regions of very high heat flux, and (4) thermo-mechanical flaking of thin films on plasma facing surfaces. The database developed for this analysis did not include discharges taken soon after entry vents and so is unlikely to be influenced by dust left behind after in-vessel maintenance activity. Grafoil is made from carbon fibers of diameters >1 μm and is, therefore, unlikely to be the source of dust reported here, since modeling of the observed pulse height distribution of the Rayleigh scattered light, reported in Ref. 5, indicated dust diameters are small compared to a micron. The strong dependence of dust observation rate on injected beam power indicates that its origin is related to heat flux going to the plasma-facing wall and would suggest either ablative processes or thermo-mechanical flaking of thin films.

The observation that dust appearance rate in the upper SOL increases sharply after a switch from a period of LN-dominant operation to UN-dominant operation is suggestive of film flaking as an important source of dust in this region. During the period when the plasma is operated in LN, the upper surfaces receive a flux of cold plasma, consisting primarily of deuterons, with significant carbon ion impurity. Such a cold plasma flux is known to produce redeposition of soft C:D films with poor thermo-mechanical properties [9]. When the plasma operation is switched to UN, the power flux to these upper surfaces, now coated with soft films, is suddenly increased dramatically. It seems quite reasonable to assume that resulting thermo-mechanical stress produces flaking of the soft films and results in the increased observation of dust.

Disruptions are implicated as a contributor to dust observed in the lower divertor region due to the small increase in the dust appearance rate in the lower divertor following disruptions. The concomitant decrease in dust appearance rate in the upper SOL following disruptions may indicate that disruptions actually serve to remove dust-producing films from the majority of the plasma facing surfaces, but the removal is in the form of dust which accumulates in the lower divertor and waits to be dislodged in subsequent shots.

4. CONCLUSIONS

Submicron dust observation rates in DIII-D increase with increasing beam power in both the upper SOL and lower divertor. Little or no correlation is seen with plasma current or line averaged density. The sharply increasing rate in the upper SOL when operation is switched from a period of LN dominance to UN dominance indicates that soft film buildup on the upper surface during LN operation may be an important source of dust in the upper SOL. A small increase in dust appearance rates in the lower divertor after major disruptions indicates that dust is created by disruptions and settles to the floor.

The database will continue to be increased, including both new dischargers and more operating parameters. In addition, future work will include dust detection in the gas pre-fill prior to discharge initiation and inclusion of transient phases of discharges.

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