EUROPEAN FUSION DEVELOPMENT AGREEMENT

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ABSTRACT.

In this paper, we report on the observation of dusts measured by InfraRed (IR) and VISible (VIS) cameras in Tore Supra and in JET. The formation and transport of dusts in both Tokamaks during normal operation and disruptions are discussed. Dense hydrocarbon clouds, which might be a possible pathway to the formation of spherical nanoparticles, are always observed by the IR cameras inside the MARFE region in the JET divertor during the deuterium puffing phase before the density limit disruption. We suggest utilizing this phenomenon for a density limit disruption warning and safety feedback signal.

1. CREATION AND TRANSPORT OF FLAKES

Flakes are flying objects which are the most frequently observed dusts during normal operations and disruptions. Due to their high temperature, they radiate both in the infrared and in the visible region. Thus, they are easily detected by IR and visible cameras. Three different types of flaking events are observed during the plasma operation. The first takes place at the beginning of the plasma. Figure 1 shows the number of flaking events as a function of operation time (Fig.1(a)) and the locations where the events occur (Fig.1(b)) in Tore Supra (TS). The shots, including disruptions, were randomly chosen. The places of flaking are likely to be localized at deposition dominant zones on the limiter, near the neutralizer, and the armor of heating antennas. The most of the flake ejection (number of flaking events observed) in TS occurs when the plasma expands and touches the armor of the heating antennas. The arrows in Fig.1(b)) indicate the direction and relative velocity (length of the trajectory versus camera exposure time) of the ejected flakes obtained from the visible camera images. A more robust tracing of the trajectories of the fakes is a very difficult task and it cannot be simply deduced from the images: The trajectories of flakes strongly depend on many factors such as initial velocity, electric and magnetic field configuration, and size of flakes (mass and charge). In JET, such a flaking is also often observed, when the plasma touches the divertor. A lot of flakes are ejected from the divertor region. The transport of flakes in JET is likely to follow the field lines inside the divertor region. The direction of the transport, however, is very difficult to understand, too. The second type of flaking events occurs in the middle of the plasma operation. In this plasma phase, the flaking is rather “mild”, so that a statistics can not be established from the current observations: Much higher temporal/spatial resolutions for measurements would be required to resolve the individual flaking. The third type of events is connected to disruptions. Before/during/after disruptions, heavy flaking is often observed.

2. OBSERVATION OF HYDROCARBON CLOUD FORMATION.

During the disruption study in JET (e.g. Pulse No’s: 69327-69343, 70568-70584), a MARFE formation in the divertor region during the deuterium puffing is identified by IR and VIS (fast CCD) cameras, and by bolometry. The MARFE is clear recognizable even in the IR images (see Figure 2), it is speculated that a large amount of hot hydrocarbon species are concentrated in the

MARFE region. These hydrocarbons form observable “clouds” emitting also in the infrared part of the spectrum. Typically these hydrocarbon clouds start to be observed, at least, a second before the density limit disruption occurs. Thus, the density limit disruption could be forecasted by observing the hydrocarbon cloud formation in the divertor region by IR imaging. Note that the hydrocarbons are trapped in the scrape of layer and survive more than 2 seconds until disruption occurs [label 4 in Figure 2 shows the separatrix (dotted line) before the disruption (occurs at 24.177 sec.)]. The hydrocarbon clouds are transported from high field side to low field side during the detachment. This indicates that they could be a high density carbon source which might be deposited on the main chamber wall (lead to the creation of flakes). From the safety point of view, such kind of reaction has to be suppressed and controlled. At present a lot of activity is being devoted to the generation mechanisms of these clouds. By adjusting the amount of deuterium puffing rate, the formation and destruction of hydrocarbon clouds can be observed (e.g. Pulse No: 70578). In these studies, the D_α signal at the outer divertor and the hydrocarbon emission observed by IR camera are in phase with deuterium puffing rate: The more the deuterium is puffed, the higher the concentrations of the D_α and the hydrocarbons are. On the other hand, the C_{III} signal in the outer divertor is out of phase: The more the deuterium is puffed, the less the C_{III} concentration is. This might be due to the cooling of the plasma leading to the hydrocarbon formation in cooled plasma observed directly by IR camera. Furthermore, the cooling may enhance the survival time of hydrocarbons as the plasma temperature decreases. When the deuterium puffing is turned off, the hydrocarbon clouds disappear within about 310ms, the plasma does not disrupt, and reaches a steady state. This indicates the maximum lifetime of hydrocarbon clouds in the plasma. From the safety point of view, a feedback control for preventing density limit disruption has to be activated at least 310 ms before the disruption, in order to lower the density or to be sure that no observable hydrocarbon clouds are left in the plasma.

3. A POSSIBLE PATHWAY TO NANOPARTICLE FORMATION IN FUSION DEVICES

MARFEs are usually considered as volume recombination zones in tokamak plasmas. They are characterized by high density ($n_e \sim 10^{13}-10^{15}$ cm^{-3}) and low temperature ($T_e \sim 1$eV). These parameters are very close to the conditions for the dust particle formation in low temperature dusty plasmas. This hypothesis is supported by the recent modeling of Smirnov et al. for the carbon dust particles (1μm) in DIII-D [1]. These calculations provide the particle temperature, potential, and sublimation rate of carbon nanoparticle in DIII-D plasma. According to the simulations, in the parameter region of T_e below10eV and n_e in the range $10^{12}-10^{14}$ cm^{-3}, dust particles may grow and their survival time could be as long as plasma pulse duration, i.e. of the order of seconds. Comparing the modeling results with the MARFE characteristics described above, an overlap is found. This suggests a possible pathway to spherical, cauli-flower shape nanoparticle formation in fusion device. Assuming a hydrocarbon flux of 1.25×10^{16}cm^{-2}s^{-1} with 1g/cm^{-3} as a lower boundary, which was found in Ar-CH_4 dusty plasma during the hydrocarbon dust formation [2] (c.f. $\sim10^{14}-10^{15}$cm^{-2}s^{-1} for carbon film deposition [2], $1.3-3.5\times10^{16}$cm^{-2}s^{-1} in Tore Supra [3] and $10^{13}-10^{15}$cm^{-2}s^{-1} in divertor of

JET [4]), nanoparticles of ~3nm in diameter can be produced within 2 seconds with constant deuterium puffing. Note that a growth rate of ~1μm/s is also obtained from the calculations for $T_e \leq 3$eV, $n_e \sim 10^{14}\mathrm{cm}^{-3}$ (typical for detached or afterglow plasma) with 1% of carbon impurity fraction [5]. Intensive further studies are needed to increase confidence in this interpretation, however.

CONCLUSION

The formation and transport of dusts are visualized by infrared (IR) and visible (VIS) cameras in Tore Supra and in JET. The observation of MARFEs in IR camera indicates the existence of dense hydrocarbon species in the MARFE region, which can be utilized as a density limit disruption warning and safety feedback signal. Also, such dense density of hydrocarbons in a localized place with low plasma temperature might be a possible pathway to the spontaneous hydrocarbon nanoparticle formation. Evidence for such a pathway exists since long, although the formation mechanism has not been experimentally proven yet [6]. Moreover, such a high density is ITER relevant, further studies are needed to clarify their roles in ITER-like plasmas.

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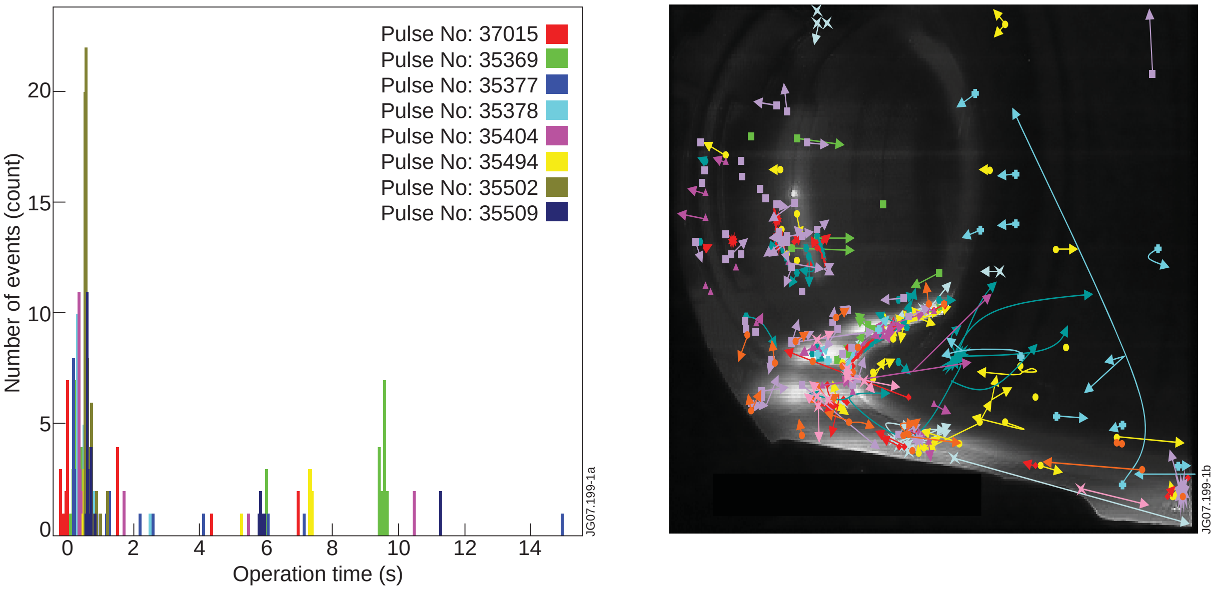

Figure 1: Number of flaking events as a function of operation time (a) and the places the events occurs (b) in Tore Supra.

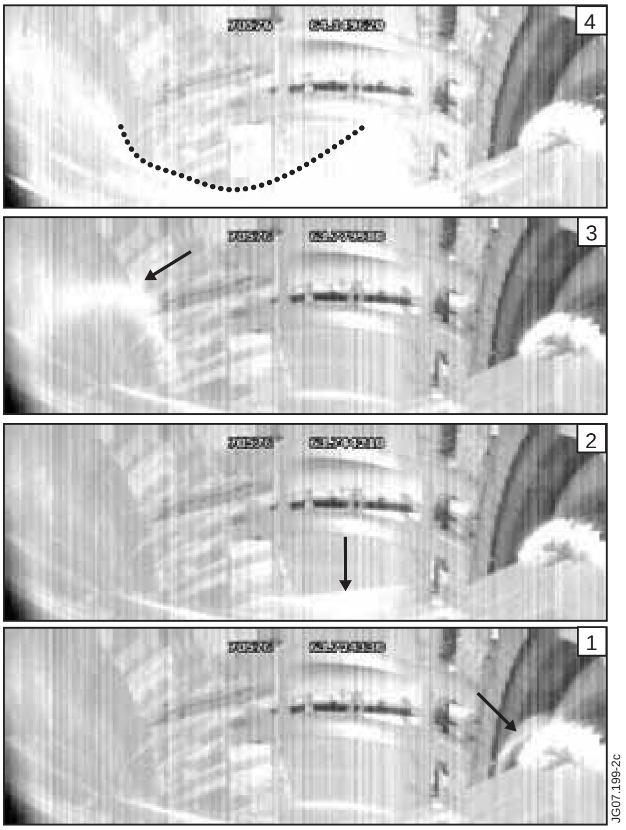

Figure 2: MARFE observed by IR camera during the density limit disruptions (Pulse No: 70576) in JET. The observation of MARFE by IR camera indicates abundance of hydrocarbons in the MARFE region.