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Detection of Dust on JET with the High Resolution Thomson Scattering Systems

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ABSTRACT.

Dust particles have been observed with Thomson Scattering on several tokamaks. We present here the first evidence of dust particles observed by the new High Resolution Thomson Scattering system on JET. The system consists of filter spectrometers that analyze the TS spectrum from 820-1062nm in 4 spectral channels. The laser source is a 5J Q-switched Nd:YAG laser. Without a spectral channel at the laser wavelength, only dust particles that emit broad band light emission could be detected, these particles have been observed on JET after disruptions. The timing of their emission is clearly different from that expected for a Thomson scattering pulse, as the light pulse from dust is much longer, it peaks after the peak of the incident light and has a long tail.

1. INTRODUCTION

Dust particles have been observed with Thomson Scattering (TS) in several tokamaks [1,2]. The laser light directly scattered by the dust particles can be observed if a suitable channel at the laser wavelength is present in the TS system, or when the light emitted by the dust particle while it is ablated or heated can be observed in the channels devoted to the TS measurements. The High Resolution Thomson Scattering System (HRTS) present on JET is not equipped with a spectral channel at the laser wavelength, so the only information can be obtained from other channels. One advantage of the JET system is that the scattered signal detected by avalanche photodiodes is fully recorded with a sampling rate of 1 ns, enough to catch the dynamics of the dust ablation. In the following we are going to illustrate the TS system present on JET, the characteristics of the light coming from the dust and the behaviour of the dust after disruptions in a typical discharge.

2. HRTS SYSTEM

The HRTS diagnostic on JET has 21 spectrometers; in order to improve the spatial resolution, up to 6 fibres of three different lengths (corresponding to three different positions in the plasma) go into each spectrometer [3]. The fibres are of different length so that the light from different spatial points can be distinguished by temporal delays (~150ns). Up to 63 spatial points are then measured, each with a spatial resolution of 15mm. Each spectrometer has four spectral channels that look at different parts of the spectrum; interference filters are used to separate the spectral components of the TS signal. No spectral channel is looking at the laser wavelength. The signal from each detector is acquired for 500ns with a sampling rate of 1ns. The signals coming from each detector are analysed by fitting them with up to three gaussians, one for each delay fibre. The position and width of the gaussians are measured during the calibrations and kept fixed during the fitting process. The amplitudes of the Gaussians obtained by the fit are the TS signals that are then used to reconstruct the temperature and the density of the plasma (see Fig.1).

The spectrometers are divided into two groups: one measures the plasma core, the other the plasma edge. The spectrometers for the plasma edge have narrower filters and are closer to the laser wavelength. In the following we are mainly concentrating on the core spectrometers. The Q-switched laser fires at 20Hz with an energy per pulse of 5J and the pulse duration is about 15ns. It produces

two twinned, vertically offset, laser beams that are injected in the tokamak from an equatorial port while the scattered light is observed at 90 degree from the top of the vessel.

3. ANALYSIS OF THE LIGHT COMING FROM DUST PARTICLES

Disruptions generally generate or raise many dust particles. These dust particles can be observed by the TS diagnostic as spurious signals with characteristics different from those of the standard TS signal. Moreover they appear after the disruption when plasma is no longer present (see Fig.2).

The time behaviour (on nanosecond scale) is also very different when we compare the TS signal and the light emitted by a dust particle. The light is not the scattered laser light, for example due to the Mie scattering, as this is at the same wavelength of the laser and we are not observing it in the present TS system. Moreover the emission from the dust particle is clearly retarded compared to the laser pulse. The shape of the scattered pulse suggests that there are two concurrent phenomena, one on a short timescale of the order of tens of nanoseconds and another on a much longer timescale (hundreds of nanoseconds). Once the signals are reported back in $\mu\text{W}/\text{sr}/\text{nm}$, all the spectral channels have almost the same amplitude (see Fig.3) this is consistent with an emission from the dust particle resembling that of a black body. To calculate the correct emission, one has to take into account the particle size and material, that may account for the small difference that can be seen among the different channels. The emission of a dust particle with a diameter of $10\mu\text{m}$ at a temperature of 4000K (assumed to be a black body) at the wavelength of 700nm is about $0.3\mu\text{W}/\text{sr}/\text{nm}$, consistent with the measurements. Mie theory [4,5], using the index of refraction of graphite found in [2], gives similar results (within a factor 0.6 to 1). The fast decrease of signal intensity, just after its peak, cannot be due only to the radiative cooling of the dust particle, so other effects as ablation of dust particle should be considered. However radiative cooling may play a role on a longer time scale, even though a full model of the dust particle ablation and cooling is necessary.

To make a more quantitative analysis of the light coming from a dust particle we have fitted the data with a function which is a sum of two decreasing functions, one fast the other slow:

$$S(t) = A_{fast} f(t, \sigma, \tau_{fast}) + A_{slow} f(t, \sigma, \tau_{slow}) \quad (1)$$

where

$$f(t, \tau, \sigma) = \frac{1}{\tau} \int_{-\infty}^t e^{-(t-t')/\tau} e^{-t'^2/2\sigma^2} dt' = \dots \quad (2)$$

$$\dots = C \exp\left(\frac{\sigma^2}{2\tau^2} - \frac{t}{\tau}\right) \left(\text{erf}\left(\frac{t}{\sqrt{2}\sigma} - \frac{\sigma}{\sqrt{2}\tau}\right) + 1\right)$$

The constant, C , has been determined in order to have the maximum of the function f equal to 1. This fitting function is just an heuristic choice, even though f satisfies the differential equation $\tau f' + f = \exp(-t^2/2\sigma^2)$ and so in a way it justifies the idea to have a slow and a fast process involved. While for a large dust particle a full nonlinear fit of all the free parameters can be done,

for small dust particles it is much better to keep σ , τ_{fast} and τ_{slow} fixed while fitting only the parameters A_{fast} and A_{slow} . The fitting will be linear and so it will be quite quick. It will also be less sensitive to noise and even a null signal (when dust is not present) can be reliably measured. The signal in each spectral channel is the sum of that arriving from the three delay lines and so we have to fit it with a sum of three $S(t)$ functions one for each delay line:

$$S_i(t) = S_1(t-t_1) + S_2(t-t_2) + S(t-t_3) \quad (3)$$

Where $t_2 - t_1$, and $t_3 - t_2$ are the delay between the three delay lines. As the dust signal we have chosen to use $A_{\text{tot}} = A_{\text{fast}} + A_{\text{slow}}$ which is close to the peak value of the function $S(t)$ if dust is present, but it is also well defined if no dust particle is present. Assuming that the dust size distribution is not changing with time, and that enough dust particles are hit at every laser pulse, the dust signal averaged on all the core spectrometers is roughly proportional to the dust density, even though the correct proportionality factor is not known. In the following analysis we have fixed the value of σ , τ_{fast} and τ_{slow} to: $\sigma = 9.5\text{ns}$, $\tau_{\text{fast}} = 25\text{ns}$, and $\tau_{\text{slow}} = 740\text{ns}$. The result for a discharge can be seen in Figure. 4.

It can be clearly seen that the dust is decreasing after the disruption and almost disappears after 1.5s. This time is not much different to what can be obtained assuming that the dust is falling in the gravitational field. Other shots give similar results. In some shots there are some asymmetries between the more central spectrometers and the spectrometers looking more towards the edge, but at the moment they are not conclusive.

4. SIGNAL DISTRIBUTION

The experimental cumulative distribution function of the signal is shown in see Fig.5

A preliminary estimate of its characteristics has been done at least for the tail of the distribution which appears to follow a power-law:

$$P(S) = \frac{\alpha - 1}{S_0^{1-\alpha}} S^{-\alpha} \quad (4)$$

where S_0 is the cut-off of the power-law distribution. For this particular pulse number, the coefficient α is about 3.28, while other shots have a coefficient α between 2.5 and 5. The bulk of the distribution is clearly not a power-law, a model for the particle ablation and heating is needed in order to relate it to the distribution of dust particle size. The coefficient of the distribution has been estimated following [6].

CONCLUSION

Dust has been observed by the JET High Resolution Thomson Scattering system after disruptions. The light is emitted by the dust particles and is not scattered laser light. The intensity is compatible with the expected dimension of dust grains, but a model of the dust ablation and cooling is still

needed. Nevertheless the data can be fitted with a simple function having two timescales. Averaging the values of the peaks in the signal traces over all spectrometers we can have an estimate of the dust content (at least within an unknown proportionality factor). The dust lasts for about 1.5 seconds after the disruption. This is compatible with a ballistic behavior of the dust particles. A preliminary distribution of the signals has been obtained, even though a full model of the dust ablation is needed to relate it to the dust size and density. It can be clearly seen that the dust is decreasing after the disruption and almost disappears after 1.5 s. This time is not much different to what can be obtained assuming that the dust is falling in the gravitational field. Other shots give similar results. In some shots there are some asymmetries between the more central spectrometers and the spectrometers looking more towards the edge, but at the moment they are not conclusive.

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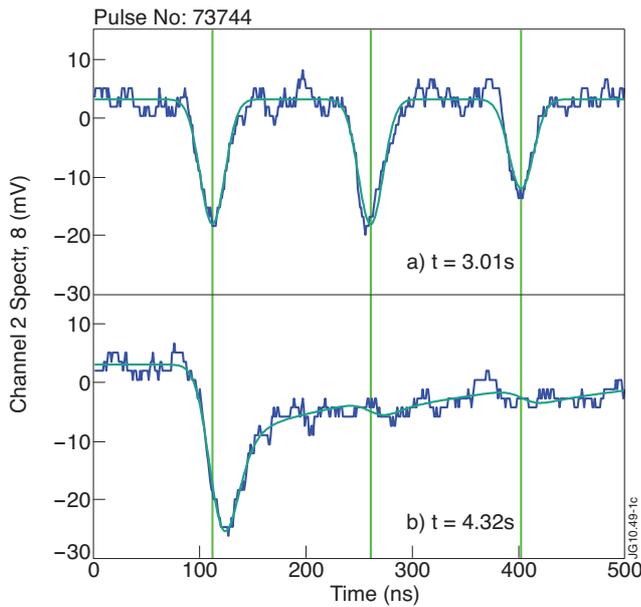


Figure 1: a) JET Pulse Number 73744, time trace acquired in presence of plasma: the three peaks are TS signals coming from three spatial position delayed by about 150ns from each other. b) signal observed in the presence of dust. The peak of the signal is delayed by about 10ns compared to the TS signal. The vertical lines correspond to the laser pulse time measured during the calibrations.

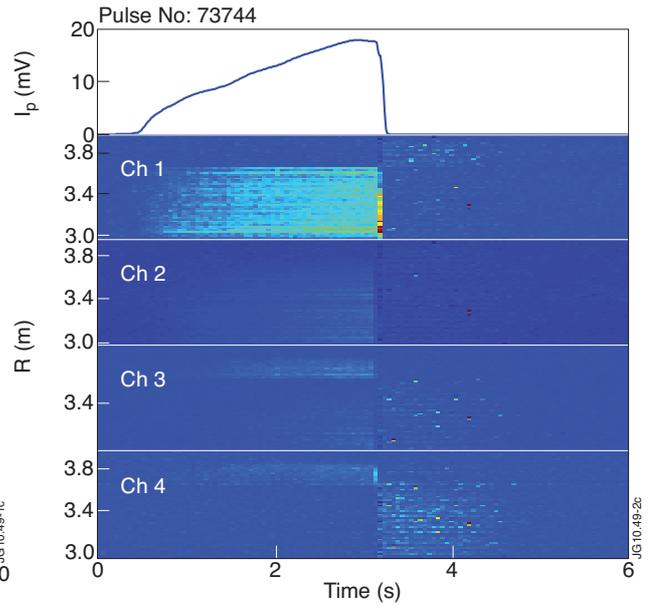


Figure 2: Plasma current and the signals from the 4 channels of the HRTS system. Before the disruption ($t = 3.3s$) the TS signals are visible, after the disruption the irregular dots are related to the dust. The color indicate the signal intensity. In the edge spectrometers ($R > 3.64$) the 4th channel is the closest to the laser wavelength. The trace at the top shows the plasma current, indicating that the plasma has been extinguished.

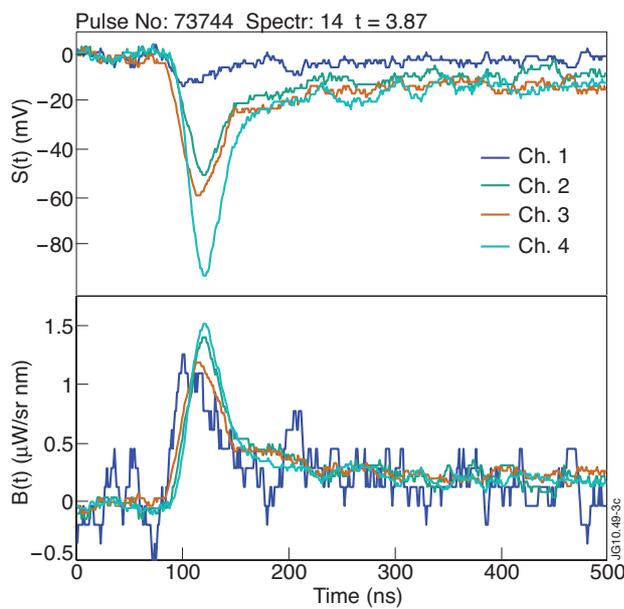


Figure 3: Top: the signal of a dust particle in mV, bottom: the same signal in $\mu W/sr/nm$. An almost flat spectrum is assumed.

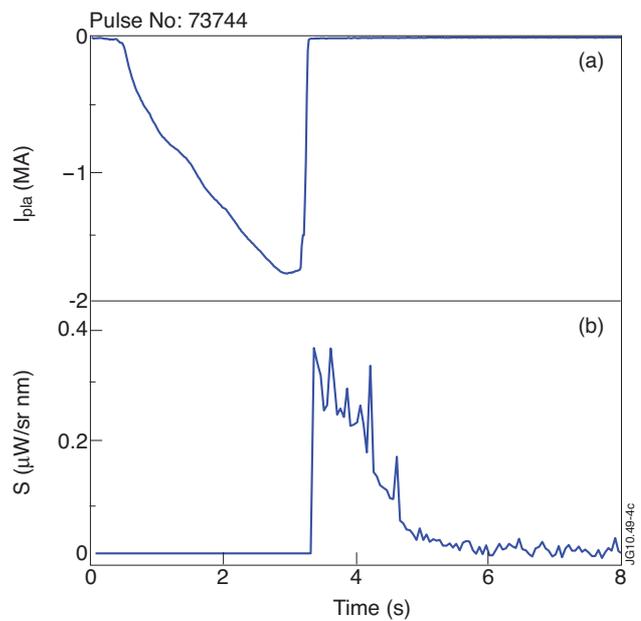


Figure 4: a) Plasma current for the JET pulse number 73744, b) Average dust signal of the 4th spectral channel of every core spectrometer.

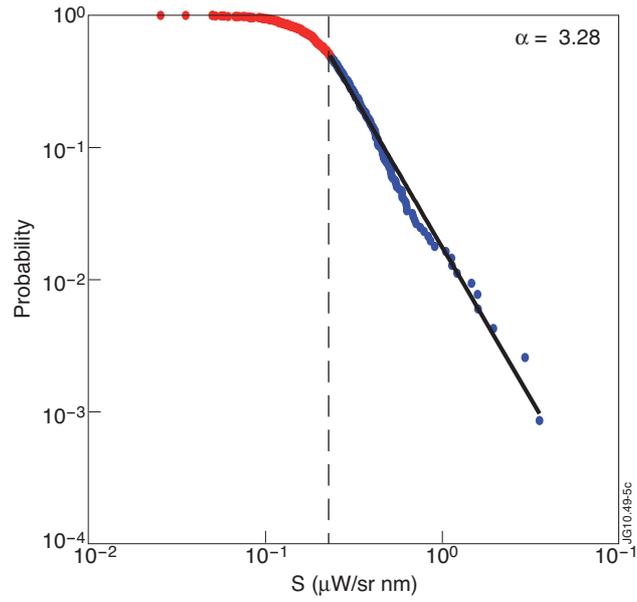


Figure 5: Experimental cumulative distribution of the dust signal. The tail of the distribution is fitted with a power-law (in black). The bulk (in red) deviate clearly by a power-law. The vertical dashed line indicate the chosen cut-off of the distribution.