*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, O-5.005 (2007)*

Fluorescent Microspheres as Tracer Particles in Finite Dust Clusters

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The use of tracer particles to follow the dynamics of a system is a standard technique in fluid, combustion and aerosol science, in medicine, technology and many other fields (see e.g. [1]). Tracer particles are most commonly used when the actual moving species (like atoms and molecules in liquids or gases) cannot be visualized directly. Then tracers are inserted that are considered to mimic the motion of an ensemble of flowing atoms/molecules.

We have developed a tracer particle approach with fluorescent microspheres to be used in dusty plasmas [2]. In contrast to the above mentioned systems, here the tracer is identical to the investigated species, besides its fluorescent properties: The tracer forms an integral part of the system and consequently exactly reflects the dynamics of the system. Our technique is of use e.g. when the dust motion is so fast (e.g. in dust streams) that an unambiguous tracking of many particles becomes impossible. This is usually the case when the traveling distance of the particles from one image to the next is larger than half the interparticle distance. An alternative application is in systems with very high particle density or in 3D systems where overlapping particle images occur and the identification of individual particles becomes problematic.

Dusty plasmas show a rich dynamical behavior that is studied here by the tracer particle approach. In dusty plasmas, microspheres are trapped in a plasma discharge where the particles acquire high negative charges due to the inflow of plasma electrons and ions. The tracer particle technique is illustrated using a two-dimensional (finite) dust system which is vertically confined to a flat cloud by the force balance of gravitation and electric field force.

The experiments have been performed in a parallel plate rf discharge in argon at a discharge pressure of 7 Pa and a discharge power of 3 to 11 W at 13.56 MHz. First, (usual) monodisperse white MF (melamine formaldehyde) microspheres (8.11 μm diameter) are dropped into the plasma where they are trapped in the space charge sheath above the lower electrode.

Subsequently, a single tracer particle is dropped into the discharge. The tracer particle is a MF microsphere doped with a fluorescent dye, ethidium bromide in our case. The

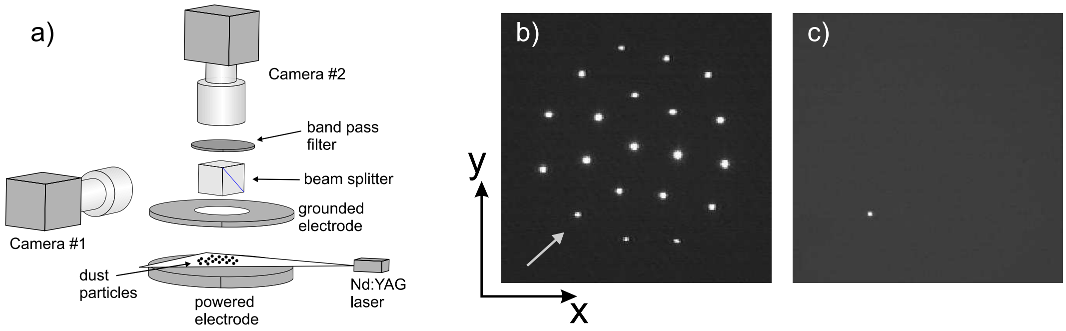

Figure 1: a) Scheme of the experimental setup. One of the trapped dust particles is the fluorescent tracer particle. See text for details. b) and c) Snap short of the dust cloud. (b) Image of camera #1 with all particles and (c) image of camera #2 that only sees the fluorescent tracer particle. In (b) the position of the tracer is marked by the arrow.

fluorochrome ethidium bromide has a broad excitation spectrum with two maxima at about 300 and 530 nm. The emission spectrum ranges from about 550 to 750 nm with a maximum near 600 nm.

Our fluorescent particles have a diameter of 8.07 μm which is almost exactly identical to the white MF particles. Thus, the fluorescent tracer particle is trapped at the same height in the plasma as the white particles and is an intrinsic part of the entire dust system. Hence, the tracer particle is a perfect representative of all particles in the cluster.

The (white and fluorescent tracer) particles are illuminated by the beam of a Nd:YAG laser at 532 nm (with a power of 200 mW) that has been expanded into a line by a cylindrical lens (see Fig. 1). The Nd:YAG laser also excites the fluorescence of the tracer particle.

The scattered light is viewed from top by two CCD cameras. Camera #1 collects the unfiltered scattered light and thus sees all particles (white+fluorescent). Camera #2 is equipped with a filter blocking the spectral range between 520 and 532 nm, thus suppressing the light from the exciting Nd:YAG laser. Only the fluorescent emission of the tracer particle is seen by camera #2.

Figure 2 now shows the motion of the tracer particle in a 2D dust cluster with about 250 particles. However, a few white MF particles are suspended in a sheet below the actual crystal plane. These lower layer particles are susceptive to an instability driven by the ion streaming motion in the sheath (see e.g. [3, 4]). The instability of the lower particles in turn heats the upper-layer particles. With increasing discharge power the heating increases [3].

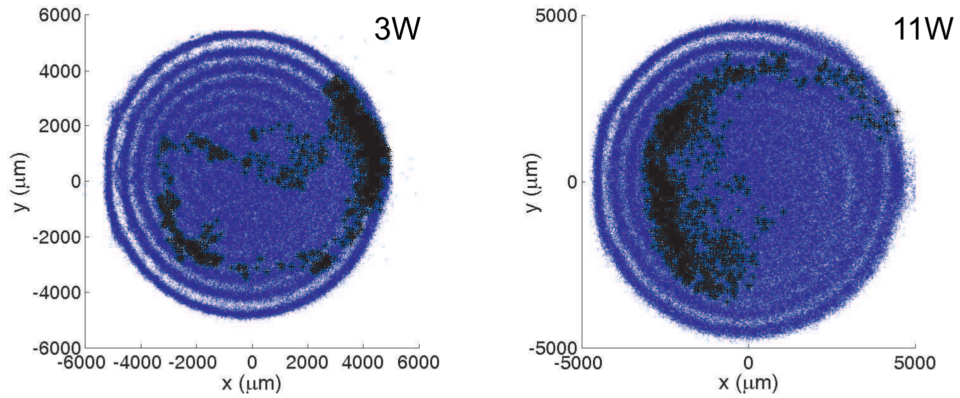

Figure 2: Left: Motion of the tracer particle (black) over 30 minutes. The blue dots correspond to the positions of the other particles in the cluster with $N \approx 250$. Here, a discharge power of 3 W is used, where the cluster is in a fluid state close to crystallization. Right: Same for 11 W in a fully developed fluid state.

This allows to control the effective temperature of our crystal.

In Fig. 2 the tracer motion is shown for two fluid regimes, namely at 3 W near the crystallization point and at 11 W in a well developed fluid state. The motion is recorded at a low frame rate of 1 fps which enables to record the particles for a very long time. At 3 W the tracer stays for a long time in a quite small region at the outer boundary of the crystal. Then it performs a circular orbit ending near the starting point. At 11 W a more extended tracer trajectory is observed that also shows an overall rotary motion.

We now have calculated the diffusion properties of the tracer particle in the two situations. As a standard method the mean square displacement (msd) $\langle(\vec{r}(t) - \vec{r}(0))^2\rangle$ is analyzed (see e.g. [5]). In normal diffusion, the msd obeys a power law $\propto t^\alpha$ with $\alpha = 1$. Superdiffusion and subdiffusion yield exponents α larger and smaller than 1, respectively. Figure 3 shows the msd derived from the fluid regimes at 3 W and 11 W. For $t < 50$ s, approximately, nearly a normal diffusion regime is found whereas for larger times a decisive deviation is observed. Here, the fluid near crystallization at 3 W shows a superdiffusive behavior with $\alpha \approx 1.5$ wheras the full fluid state shows a more subdiffusive regime with $\alpha \approx 0.5$. Normal diffusion and superdiffusion have previously been reported for dusty plasmas [5].

A detailed interpretation of the results measured here is however complicated by the fact that the heating of the crystal plane is locally concentrated in its central region. Nevertheless,

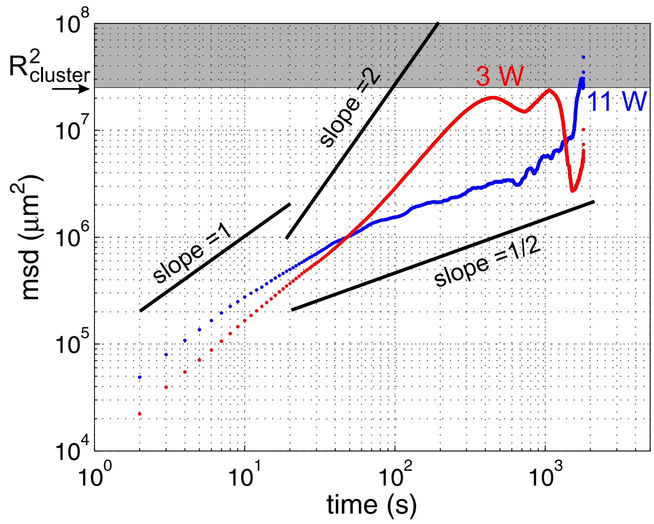

Figure 3: Mean square displacement as a function of time. See text for details.

the diffusion properties have been measured for times (about 30 minutes) that have not been achieved in previous studies [5]. Thus, the diffusion on very long time scales become accessible in these tracer experiments. During these long times, the tracer traversed the entire cluster and consequently a change of the diffusion properties is observed (near $t = 400$ s at 3 W and $t = 1000$ s at 11 W).

Summarizing, we have presented a tracer particle approach to investigate the dynamics of dusty plasmas. The tracer technique has been applied to fluid dust clusters recorded at a very low frame rate allowing for very long-duration experiments. The diffusion properties of the tracer in a fluid near freezing and a fully developed fluid are determined. For long times, the diffusion changes from normal diffusion to superdiffusive and subdiffusive, respectively.

This work is supported by DFG via SFB-TR24 Grant A3.

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