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Laser Manipulation of Particles in Dusty Plasmas under Microgravity

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Dusty plasmas consist of micrometer sized particles immersed in a gaseous plasma of electrons, ions and neutrals. Such systems are ubiquitous in astrophysical situations, they have strong technological applications and are especially interesting for fundamental plasma physics: in these systems the dynamics of the microspheres can be followed on a kinetic level by video microscopy [1]. Under laboratory conditions the dust systems are confined in the plasma sheath to mainly 2D structures by the force balance of electric field force and gravity. Under microgravity conditions, large 3D dust clouds are found in the plasma volume. Nevertheless, the 3D dust clouds are hampered by dust free regions ("voids") in their center. The mechanism of the dust confinement and the formation of voids under microgravity conditions is not adequately understood so far.

Experiments on dusty plasmas under microgravity conditions have been performed on parabolic flights (by MPE Garching, University Kiel, University of Iowa) and on the International Space Station ISS (by MPE Garching / IHED Moscow). The main diagnostic tool is the observation with video cameras. Although the parabolic flight experiments of the University Kiel contained a Langmuir probe, an essential device for individual particle manipulation in the plasma is lacking.

We have developed and tested a laser manipulation system to be used for dusty plasmas under microgravity. Laser beams are ideally suited to manipulate individual dust particles in dusty plasmas [2, 3, 4]. The manipulation system consists of a galvanometer scanner, an optical focus system, a manipulation laser and a digital control unit. The manipulation system will be tested on parabolic flights in 2005 and 2006. The system is intended to be used on the international dusty plasma experiment IMPACT aboard the ISS.

Here we will show the concepts of the experimental configuration and first results of measurements and manipulation of dust particles under laboratory conditions.

Experimental setup: The scheme of the experimental setup is presented in Fig. 1. The manipulation laser is a Nd:YAG laser with a wavelength of 532 nm and a maximum output

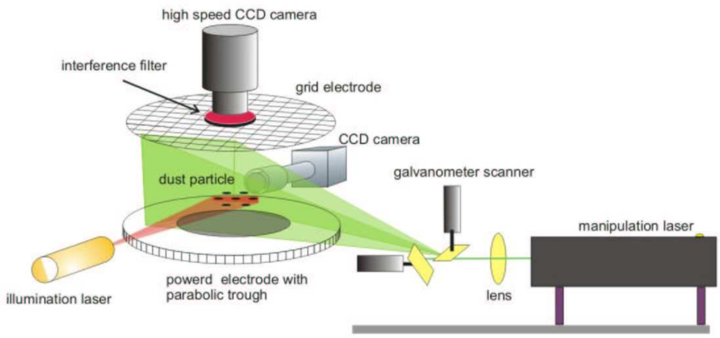

Fig. 1: Scheme of the experimental setup.

power of 200 mW (TEM_{00}, multi mode). With a lens system of focal length $f = 200$ mm, the laser beam is focused into the center of the plasma chamber where the dust particles are trapped. The laser beam is steered by a two-axis galvanometer scanning system. The two mirrors can be controlled independently, thus the beam can be moved to an arbitrary position inside the plasma. The mirror motors are computer-driven by means of a multi-I/O card.

The laboratory experiments for testing the manipulation device were performed in a parallel plate RF discharge in argon at 13.56 MHz and an RF power between 1 and 100 W. Plasma crystals were formed using monodisperse polymer particles with a diameter of 9.55 μm and 7.17 μm. The particles are dropped into the plasma where they attain a negative electric charge of several thousand elementary charges. In the plasma sheath, the particles arrange in a monolayer crystal of approximately 50 mm diameter, 20 mm above the lower electrode.

The particles are illuminated by an expanded laser beam of a laser diode (665 nm, 50 mW). This expanded beam is much weaker than the manipulation laser and does not affect the dust particles. The particle motion is recorded with a high-speed CMOS camera with a maximum frame rate of 500 frames per second. The camera is equipped with an interference filter at 665 nm to suppress the manipulation laser light.

Heating and Melting: In this laboratory experiment we tried to heat the plasma crystal by the laser manipulation device. Therefore, the laser beam was focused randomly onto different dust particles in the crystal. The vertical scanning mirror was kept at a constant position, whereas the horizontal scanner was moved randomly. The heating laser power was increased from 0 to 200 mW in this experiment.

The experiments have been performed at a gas pressure of 7 Pa and a discharge power of

P_{rf} = 8 W. Here, we used the particles with 7.17 μm diameter.

Figure 2 shows the trajectories of the particles for different laser heating powers in a crystal of 33 particles. The temperature of the dust particles is shown in Fig. 3. It is seen that

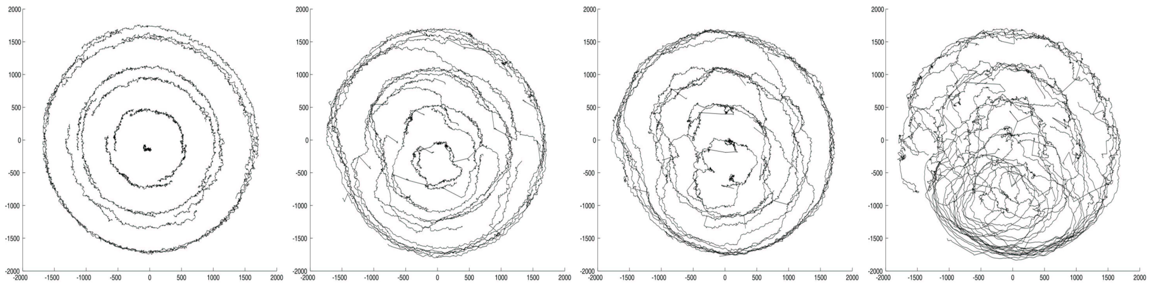

Fig. 2: Particle trajectories at a laser power of 0, 50, 60, and 200 mW.

the particle temperature dramatically increases by a factor of 6 with laser power. The main increase is obtained around a laser power of 60 mW. At higher laser powers the temperature saturates because vortex-like particle motions are induced by the laser.

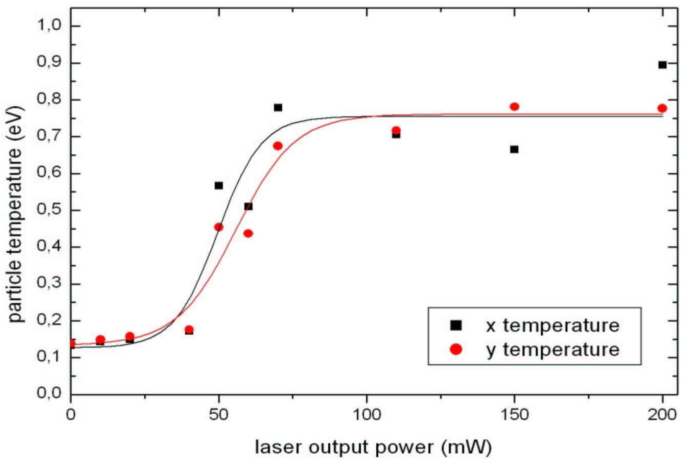

Fig. 3: Particle temperature as a function of laser power.

Mach Cone Experiment: In a second experiment, we have produced Mach cones in single layer crystals. For this purpose, the laser was focused onto the particles in the crystal under a small angle. Here, the horizontal scanner was kept at a fixed position and the vertical scanner was moved at a constant angular velocity. The particle size was 9.55 μm and the gas pressure 7 Pa.

Waves in the plasma crystal are excited by the radiation pressure of the laser beam. By moving the laser spot with a supersonic velocity through the crystal a series of circular wave-fronts are excited which superimpose to form a Mach cone [5, 6]. The opening angle of the

Mach cone μ is determined by the Mach cone relation $1/\sin(\mu) = M$ with $M = v/c$, where v is the supersonic speed of the laser spot and c the acoustic speed of dust lattice waves in the plasma crystal. The propagation of the Mach cone in the crystal is shown in Fig. 4. One can easily identify the Mach cone moving from the lower left corner to the upper center. The opening angle is determined to be 23.5° at a laser velocity $v = 55$ mm/s. Thus, the sound speed is measured to be $c = 21.9$ mm/s. From this the dust charge is found to be $Z = 14\,100$ at a screening strength of $\kappa = 1$.

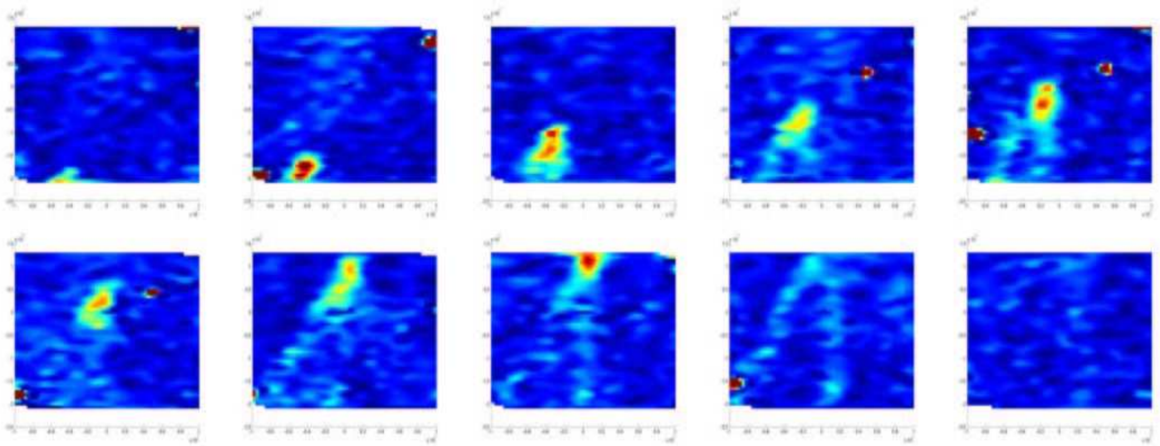

Fig. 4: Pseudocolor representation of the dust particle speed. A Mach cone is formed in the plasma crystal.

Summarizing, we have presented the setup of a flexible and versatile laser manipulation device that is designed to be used under microgravity conditions. We have successfully applied the manipulation system to two different experiments in the laboratory which demonstrate the efficiency of the system.

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