'PK-4' – Laser-driven shear flow in a DC discharge complex plasma

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Abstract. Flows, shear flows, laminar and turbulent flows on the microscopic scales are one of the fundamental issues in fluid dynamics. Due to their special properties, complex plasmas provide an excellent opportunity to study these flows, even on the scale of individual particles. To this end, experiments were conducted in the 'Plasmakristall 4' (PK-4) experimental device that uses the positive column of a high voltage DC discharge to produce complex (dusty) plasmas. The linear geometry of PK-4 provides the opportunity to study all these kinds of flow phenomena as well as waves and collisions. Since gravity distorts most of the effects to be studied with PK-4, the facility is planned to be operated onboard the International Space Station ISS from 2008. In order to generate a high-velocity shear flow PK-4 is now upgraded with a 20W manipulation laser system.

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FROM LAMINAR FLOW TO TURBULENCE

One of the key questions in fluid dynamics is still the transition from laminar flow to turbulence. The investigation of the dynamics of single particles in a flow in the regime of this transition may lead to a break-through in this field. Can we achieve this with the PK-4 experiment?

To answer this we have to estimate the Reynolds number *Re* that we can achieve with PK-4 and compare it to the critical Reynolds number $Re_{\rm crit}$ for turbulence, which is in the range of 1200 – 20000 cm/s (strong to weak perturbation). *Re* is defined by $Re = 2Rv/n$, where *R* is the tube (flow) radius, *v* the flow velocity, and *h* the kinematic viscosity given by $h = s/n$ with the viscosity *s* and the mass density *n*. With typical values for PK-4 (R = 1.5cm, v = 1cm/s, $s = 10^{-7}$kg/ms [1], $n = 3.10^{-10}$kg/m^3) we get *Re* = 90. This means that with the typical settings we won't get turbulent flow. But we will be able to reach this regime with different settings in addition with the manipulation laser system that will generate higher flow velocities (with sharp interfaces) as a next step in the system development.

THE PK-4 EXPERIMENT

The PK-4 project is planned to fly a DC discharge tube (additionally equipped with movable RF inductive coils for particle confinement and manipulation) on the ISS in order to conduct complex plasma experiments under microgravity conditions (fig.1). The linear design of PK-4 (compared to the RF chambers previously flown on the ISS [2-4]) allows the study of the fluid-like flows of microparticles inside a complex plasma, produced in the positive column of the DC glow discharge, on the kinetic level of single particles. The glass tube also provides a better optical access for observation, diagnostics, and laser manipulation of the particles. The main part of the tube has a length of 35 cm and an inner diameter of 3 cm. 2 optical ports offer access for laser illumination and manipulation, 4 dust dispensers allow the use of different microparticles. A gas supply system with adjustable gas flow ensures the purity of the gas (Neon) and offers an additional way of introducing flow to the complex plasma. 2 CCD cameras digitally record the microparticles with a rate up to 233 fps. [5]

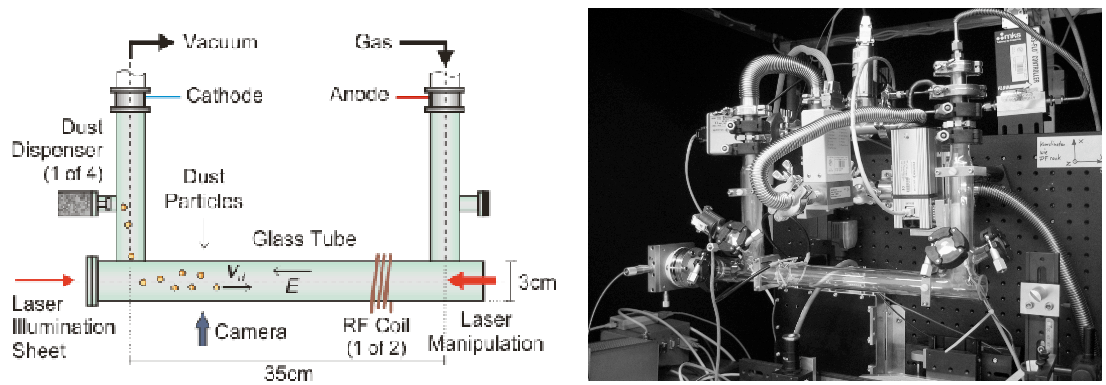

FIGURE 1. *Left:* Sketch of the PK-4 experiment. *Right:* Lab setup at the MPE; DC plasma chamber (glass tube) with gas system and manipulation laser entry (fiber entering at the left side).

The project is conducted in close collaboration between the MPE in Garching, Germany, and the Institute of High Energy Densities (IHED) of the Russian Academy of Science in Moscow.

The PK-4 Manipulation Laser

In order to produce strong shear flows we upgraded the PK-4 lab setup with a 20 W IR laser system. The diode laser module is compact and energy efficient, suitable for a future application on parabolic flights and the ISS. Due to the good efficiency the module does not need to be cooled actively. The beam (wavelength: 915 nm) is coupled into the plasma chamber by an optical fiber (see fig.1, right). The beam diameter inside the plasma can be varied between 5 and 1.5 mm, resulting in a maximum laser power of 10 W/mm^2 acting on the particles. This value will result in particle velocities in the range of some centimeters per second with a high velocity gradient at the interface.

Laser-induced Shear Flow

First experiments with the manipulation laser show promising results. A typical experiment in a complex plasma is shown in figure 2 (left): A cloud of (3.4µm MF) particles is trapped in an ellipsoidal plasma produced with a RF coil. (DC is off.) The laser output power can be adjusted nearly linearly with the supply current. The manipulation laser accelerates the particles in the center (1.5 mm ø) of the cloud to the right, whereas the particles on the outside slowly drift back (to the left) to close the loop. The laser-induced velocity is clearly depending on the laser power, as one can see in figure 2 (left – top image: 3.8 W/mm^2; bottom: 8.2 W/mm^2) where 4 single video images are superposed. The length of the particle tracks is a measure of their velocity. The result meets the expectation, since the force produced by light pressure depends on the cross section area of the particles ($F_L \sim a^2$), which is also true for the (opposite) gas drag force ($F_D \sim a^2$). This linear relation is measured and shown in the figure 2 (right).

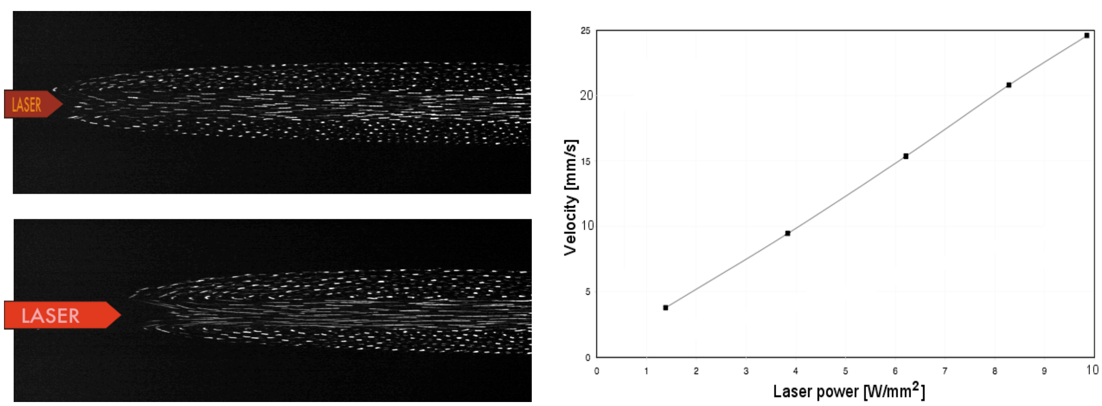

FIGURE 2. *Left:* Influence of different laser power on the velocity of particles in a complex plasma (superposition of 4 video frames), 3.8 W/mm^2 (top) and 8.2 W/mm^2 (bottom image). From the length of the tracks we derive the particle velocity. *Right:* Particle velocity depending on the laser power at a gas pressure of 80 Pa.

SUMMARY & OUTLOOK

The PK-4 experiment is suitable for producing and investigating shear flows on the kinetic level of individual particles. The flow velocity can be manipulated by different means, that is gas flow or laser manipulation, the latter being the most promising for producing also turbulent flows. The tested laser drive shows the best particle acceleration with the highest velocity gradient.

The next steps will be the implementation of the laser manipulation in the parabolic flight setup of PK-4 and the measurement of fluid properties of the complex plasma, as e.g. viscosity. This is just the beginning!

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