Shear flow and other observations in a complex plasma with 'PK-4'

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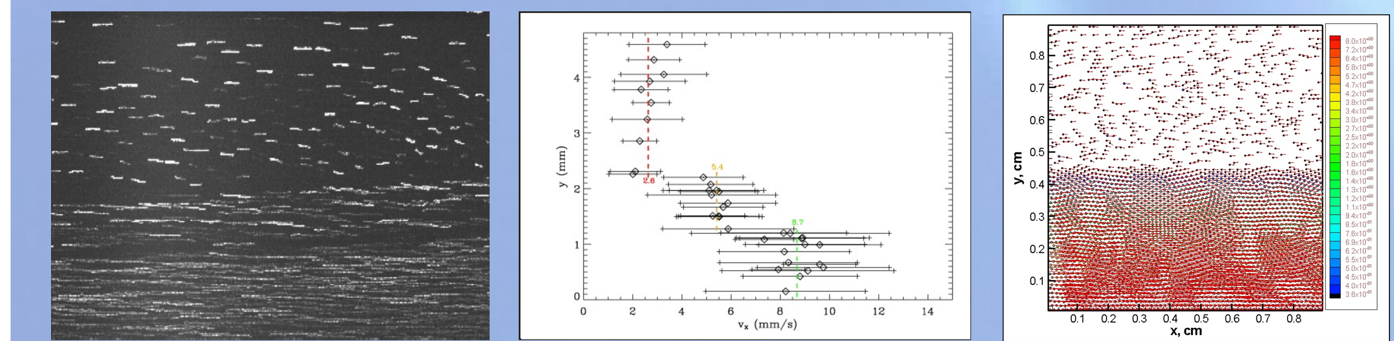
ABSTRACT: Flows, shear flows, laminar and turbulent flows on the microscopic scales are one of the fundamental issues in fluid dynamics. Due to their special properties, complex plasmas provide an excellent opportunity to study these flows, even on the scale of individual particles. To this end, experiments 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. First observations in the prototype setup are presented.

Shear flow

In this experiment, a gas flow generated a velocity gradient of the particles along the tube radius, leading to a shear flow along the tube. First, a cloud of particles was injected into the discharge tube and trapped in a rf(i) discharge in the lower end of the tube. Then, a second cloud was injected and the collision of these two clouds was observed. The second cloud penetrates the first one and lane formation (see next paragraph) of the streaming particles is observed. A few seconds later, the streaming cloud breaks apart under the influence of the shear flow.

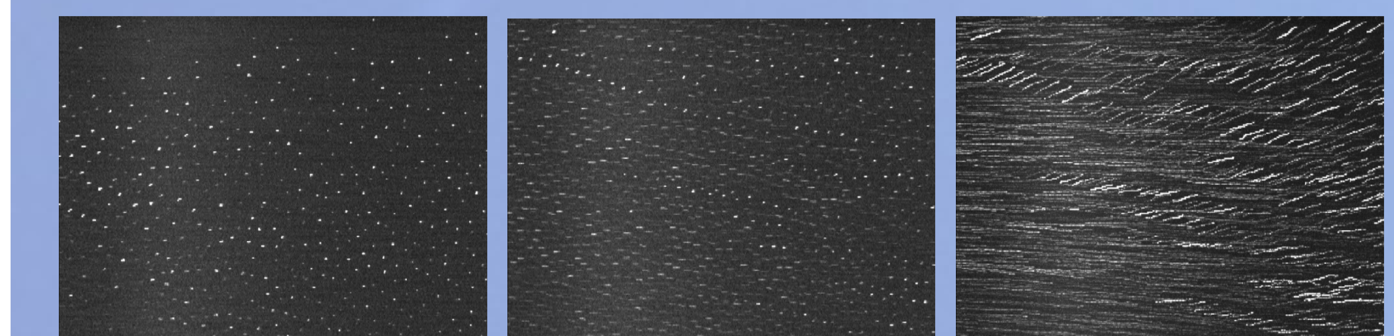


Left: Particles streaming with different velocities at different radii (10 images added up). The center of the tube is located at the lower edge of the picture, the particles are streaming down (to the right in this camera view). Center: The velocity distribution lead to a shear-off of several layers. Right: Numerical simulation of a shear flow done by B. Klumov. A shear-off of layers is observed and no Kelvin-Helmholtz instability could be found in this first simulations, which are in good agreement with the experiment. More simulation work is still in progress.

The velocity difference between the inner layer (lower edge of image above) and the intermediate layer is 3.3 mm/s, between this and the outer layer it is 2.6 mm/s. This experiment is now under investigation and computer simulations will be performed to learn something about the inner forces of this complex plasma system.

Collision and lane formation

As described in the previous paragraph, a cloud of stationary particles is observed when a second cloud impacts it. The stationary particles are not just swept away, instead they try to resist the 'invaders' by forming lanes. This effect is also known from the behavior of people walking along a pedestrian zone. To go one after the other is the most energy-saving way when penetrating a crowd. The dynamics of the formation of these lanes ('non-equilibrium phase transition', see also poster from U. Konopka et al!) can now be studied with PK-4 on the kinetic level. This, along with computer simulations, will lead to a better understanding of this phenomenon.

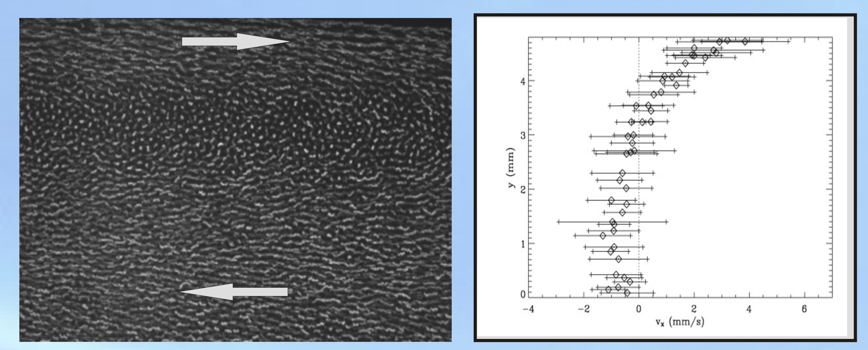


Lane formation process observed during the collision of two clouds of particles. Left: The stationary cloud before the collision (trapped in a rf discharge; down is to the right). Center: The second cloud impacts (from left to right), the stationary particles (bright spots) form lanes to resist the moving particles (grey streaks). Right: Addition of 10 single images to show the motion. Parameters are: 1400 V, 1 mA, 160 Pa (Ne), 0.5 sccm, 1.2 μm particles.

Transition from laminar to turbulent flow

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_{crit} for turbulence in the range of 1200 – 20000 cm/s (strong to weak perturbation)(M. Thomas). *Re* is defined by $Re = 2Rv/\nu$, where *R* is the tube radius, *v* the flow velocity, and ν the kinematic viscosity given by $\nu = \eta/\rho$ with the viscosity η and the mass density ρ. With typical values for PK-4 (R=1.5cm, v=1cm/s, η=10^{-7}kg/ms [1], ρ=$3 \cdot 10^{-10}$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 and which will be added as a next step in the system development.

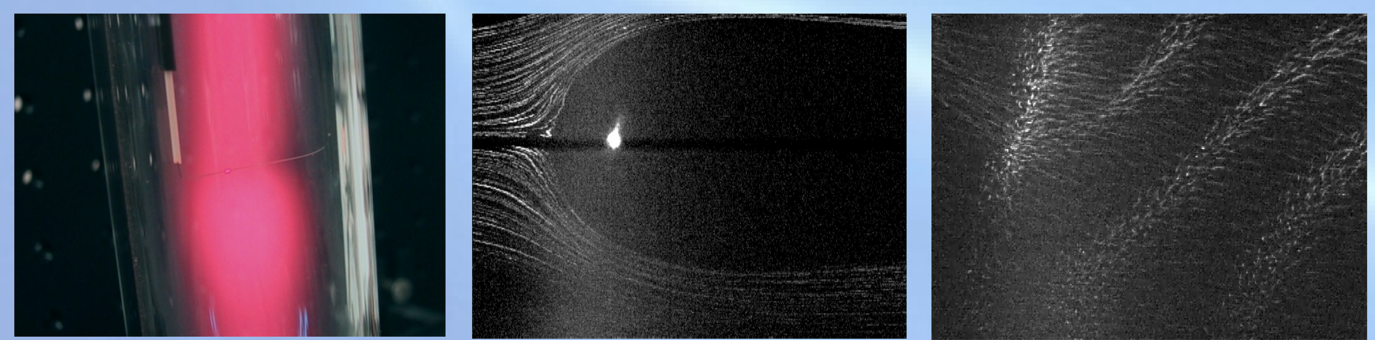


Left: A stationary 'free shear' flow in a trapped cloud of micro-particles induced by a gas flow from right to left. The center of the tube is at the lower edge of the image. The motion is rotational symmetric along the tube axis. Right: Velocity profile of the left image. The parabolic profile of the gas flow is visible in the particles.

[1] Saigo, Hamaguchi, Phys.Plasmas 9 (2002) 1210

Flow around an obstacle

Another way of introducing turbulence to a flow is to let is pass an obstacle. In this experiment a (not connected) probe wire was present in the flow and the motion of the particles streaming around the floating field of the wire (much larger than the diameter of the wire) was recorded.



Left: A probe wire inside the positive column of the dc discharge serves as an obstacle for particles streaming along the tube (downwards). Note the little red dot on the wire which is the reflection of the laser sheet on the metall. It corresponds to the bright white spot in the next picture. Center: Flow of particles deflected by the floating electric field of the wire (10 frames added). Right: Dust Acoustic Waves observed downstream of the obstacle. These waves can also be observed separately and the results which fit nicely to the theory are presented on a separate poster by Ratynskaia, Khrapak, etal.

Summary and outlook

The very first experiments with the PK-4 prototype show a huge variety of new effects and possibilities that were not achievable with the former rf plasma chambers like PKE Nefedov on the ISS. As the prototype is now being upgraded with additional hardware, like a manipulation laser, and the environment is turned into microgravity (parabolic flight campaign) more effects will be seen and more chances for new physics will arise. A promising start for a new experiment in space.

THIS IS JUST THE BEGINNING!

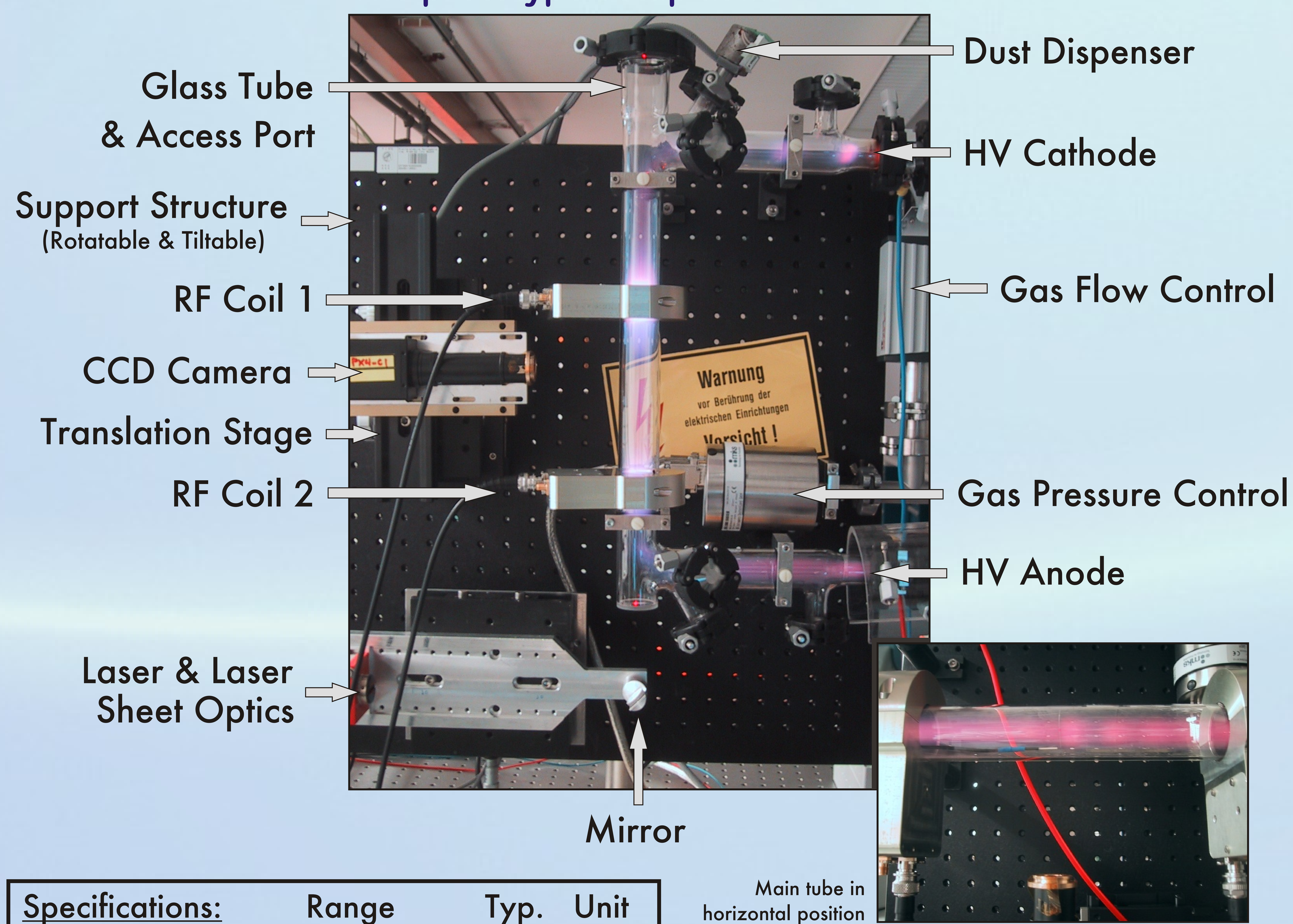
PK-4 – A DC* plasma for the ISS

The PK-4 project is intended to fly a dc discharge tube (*modified with rf inductive coils for confinement and manipulation) on the ISS in order to conduct complex plasma experiments under microgravity conditions. The more linear design of PK-4 (compared to the rf chambers previously flown, see http://www.mpe.mpg.de/pke) allows greater optical access for diagnostics as well as laser manipulation. Examples of planned experiments are "flow, shear flow, transition to turbulence" and "compression-freezing".

In the first stage of the project (Aug 2002 – Feb 2004), a laboratory and parabolic flight "pre-development" phase will be conducted. The outcome of this phase will be a laboratory/parabolic flight test model apparatus suitable for use in defining requirements and specifications of the flight model. Also first scientific results shall be achieved.

The project will be conducted in close collaboration with our colleagues from the Institute of High Energy Densities (IHED) of the Russian Academy of Science.

The prototype setup at MPE



Main tube in horizontal position

Specifications:	Range	Typ.	Unit
Main Tube Length		30	cm
Inner Diameter	2 – 3	3	cm
Overall Length (=Electrode distance)		60	cm
Pressure	10 – 260	50	Pa
Gas Flow	0 – 10	0.3	sccm
Gas	Ne, Ar	Ne	
DC Voltage	0 – 6.5	1.4	kV
DC Current	0 – 5	1.0	mA
RF Power (@ 81 MHz)	0.1 – 5	0.5	W

Features:	
Main Tube Access Port	1
Supply Ports	8
Optical Window	1
Illumination Laser	1
Manipulation Laser	Planned
Dust Dispensers (max.)	4
Support Structure Axes	Tilt, Rotate
CCD Camera (640x480, max. 150 fps)	1

Visit also our web site at http://www.mpe.mpg.de/pk4!