The project “Plasmakristall – 4” (PK–4) is a dusty plasma experiment in a combined dc/rf(i) discharge plasma under microgravity conditions

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The PK-4 experiment is a continuation of the successful dusty plasma experiments PK-1, PK-2 and PK-3 conducted on board of the orbital space stations Mir and ISS (International Space Station). The aim of the PK-4 experiment is an investigation of physical processes in complex (dusty) plasmas under microgravity conditions in a combined dc/rf discharge plasma.

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1 Introduction

During the last decade decade there has been a continually growing interest to the complex dusty plasma physics [1], [2]. A dusty plasma is a low temperature plasma with immersed dust grains of micrometer size. These grains are quickly charged under plasma exposition and become by a component of the plasma. The main features of this component are the very large and variable electric charge (up to 10^5 of electron charges) and the large mass of the grains. This leads to qualitatively new physical phenomena in plasmas - space ordering of the dust component, wide spectrum of specific kinds of dust instabilities, very low frequency (~ 10 Hz) dust acoustic waves, etc [3], [4]. In addition to the fundamental interest, the complex plasma is a unique physical object allowing to model and investigate different physical phenomena from other fields of physics on the kinetic and microscopic level - phase transitions, crystal shift deformations, shock waves and solitons, laminar and turbulent flow of highly nonideal liquid and so forth.

As a rule, the Earth gravity exerts an external stress on the dust component in laboratory experiments. To avoid this stress during some period, the experiments should be performed under microgravity conditions. Microgravity conditions can be achieved by using falling platforms, rockets, parabolic flights in air planes, or orbital flights. The PK-4 experiment [5] is a continuation of the successful dusty plasma experiments PK-1 and PK-2, performed on the Russian Mir space station [6], PK-3 [7], presently conducted on board of the International Space Station, and its successor PK-3 Plus, scheduled for 2005 on the ISS. Presently, within a predevelopment phase of the PK-4 Project (August 2002 - June 2004) supported by DLR, we design the experimental setup, perform calibrations, test experiments, and identify relevant and interesting experiments, which shall be conducted on the ISS in 2007/2008.

The aim of the PK-4 experiment is an investigation of physical processes in complex plasmas under microgravity conditions in a gas discharge chamber. Whereas PK-3 and PK-3 Plus experiments are using a planar rf capacitive discharge, PK-4 studies complex plasmas in a chamber with a combined dc/rf discharge. The PK-4 chamber will provide a particular advantage for investigation of different dynamical phenomena in complex plasmas such as sheared laminar flow of a highly nonideal dusty liquid and its transition to the turbulent regime, nozzle flow, boundary layers and instabilities, shock waves (solitons) formation and propagation, dust particle lane formation, and space dust grain separation by their size. Such a chamber will also be used as an insert for the "International Microgravity Plasma Facility" (IMPF), which shall be realized on board of the ISS within the joint project IMPF/ICAPS after 2008.

As in the case of PK-3 and PK-3 Plus, PK-4 is developed within a close collaboration of the MPE (Garching, Germany) and IHED (Moscow, Russia) scientific Teams.

2 Physical concept of the PK-4 experiment

The complex plasma experiments are provided in the Π-shape glass tube with an inner diameter of 3 cm and about 40 cm length (Fig. 1). The tube has the experimental part, (1) and the two service parts, (2) and (3). All scientific experiments will be performed in the part 1. The service parts 2 and 3 are identical. They are intended for gas and dust inlet, pumping, and the dc electrodes. The chamber can be filled with inert gases at a pressure within the range of $2 \div 266$ Pa. To produce a discharge plasma within the tube both dc discharge ($0.1 \div 5$mA) and 2 rf inductive discharges (81.4 MHz, $0.1 \div 10$ W) are used. In doing this, the positive column of the dc discharge fills uniformly the entire experimental part 1 of the tube, where the strata were found to be quickly running (Fig. 2). One rf inductor is fixed and another one is movable. All the discharges can be modulated by PC control. The local heater is intended to provide temperature gradients in the area of dusty cloud. The design is symmetrical - the inert gas can flow ($0.15 \div 12$ sccm) in both directions and the polarity of the dc discharge can be changed. Such a design allows a rich variety of active manipulations both within the plasma and the dust component. A number of dust dispensers can be installed in part 2 and part 3 to provide grain particles with different sizes and materials for specific experiments. The dust component is transported to the experimental part with a help of dc electric field or by gas flow. The dust component is illuminating by the

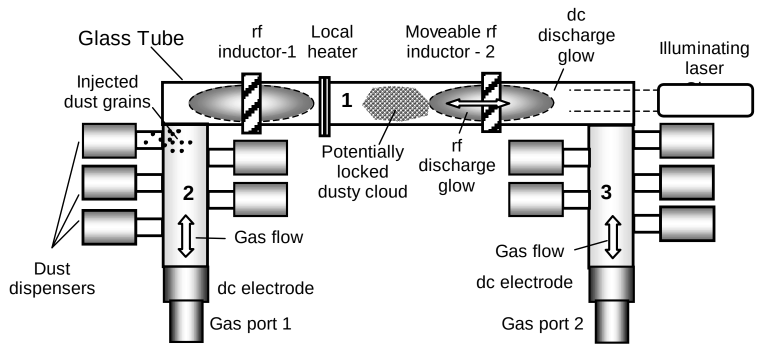
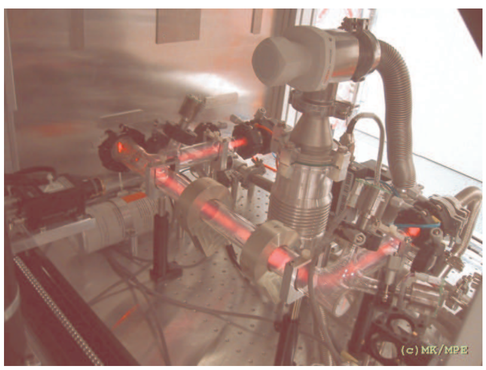


Fig. 1. General design of the PK-4 experiment: 1 - chamber area for the dusty plasma experiments; 2 and 3 - service parts.



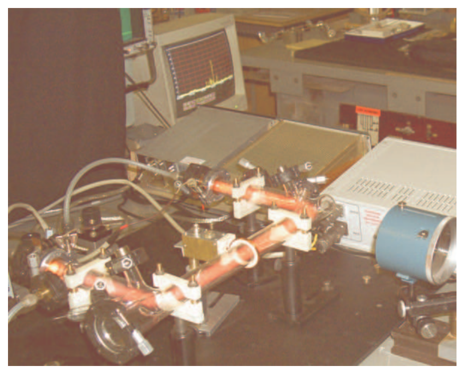


Fig. 2. Two identical PK-4 chambers: left - at the MPE lab; right - at the IHED lab.

diode laser "knife" (50 mW) and is recorded by video cameras, both from the tops and from the side of the experimental part 1.

3 Probe diagnostics of the background discharge plasma

For modelling and understanding the physical processes in the PK-4 experiments, the basic parameters of the discharge plasma were measured by a movable cylindrical Langmuir probe with a length of 4.5 mm and a diameter of 50 μm. A schematic diagram of the probe measurements is shown in Fig. 3. The probe was moved along the tube axis H and along its radius R with the help of a magnet, using a special adapter. The following plasma parameters were determined: electron concentration profiles, $n_e(H)$ and $n_e(R)$, electron temperatures, $T_e(H)$, and space potential profiles, $\varphi_s(H)$ and $\varphi_s(R)$. The main results of the probe measurements for the pure dc mode are presented in Figs. 4 and 5.

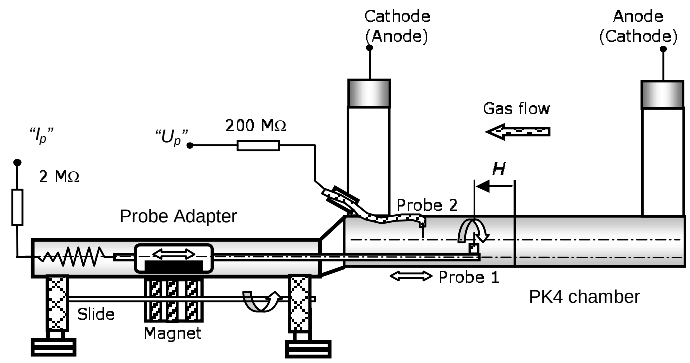


Fig. 3. Schematic diagram of the probe measurements.

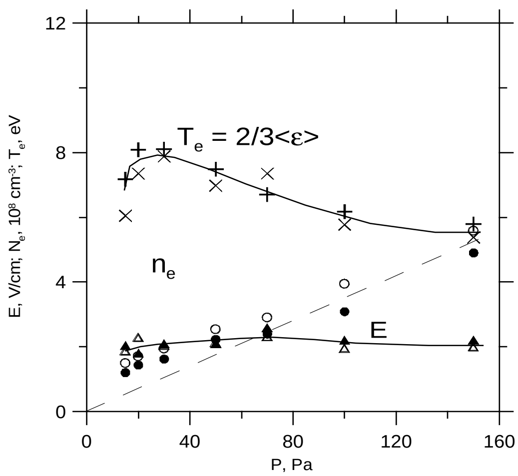


Fig. 4. Electron density n_e, electron temperature T_e, and electric field strength E, averaged on the tube axis vs neon pressure p, measured at the $I_{DC} = 1.0$ mA.

4 Spectral control of plasma pollutants

The presence of pollutant species in the discharge plasma can sufficiently disturb the plasma parameters. Even in the case, when an air leakage is almost absent, pollutants can appear from the decomposition of the glass walls and dust materials. In this connection, the quantitative spectroscopic control of the N_2, O_2 and H species was performed and the influence of these species on the plasma parameters was investigated. For this purpose, the spectral intensities of the Ne, N_2, O_2 and H spectral features were recorded for pure Ne and for Ne with 0.6%, 1.3% of air. The most useful spectral region was found to be 300 - 400 nm and especially 340 - 365 nm (Fig. 6). As it was found, the N_2 band spectral intensity is increasing and the Ne spectral line intensity is diminishing if air is present in Ne. In the low limit of air concentration, the intensity of the Ne spectral lines, I_{Ne} was found to be

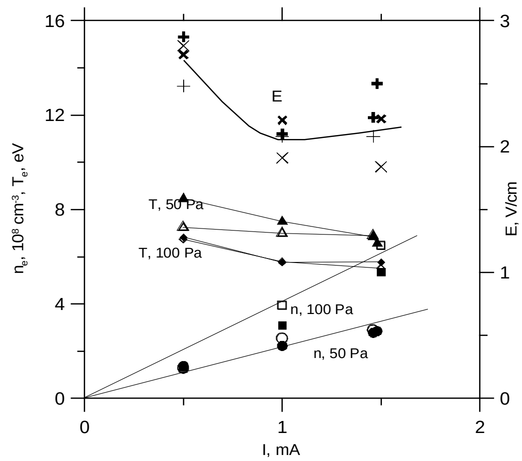


Fig. 5. Electron density n_e (circles and squares), electron temperature T_e (triangles and diamonds), and the electric field strength E (straight crosses and sloping crosses, averaged on the tube axis vs discharge current I_{DC}, measured at two neon pressures - 50 and 100 Pa, respectively.

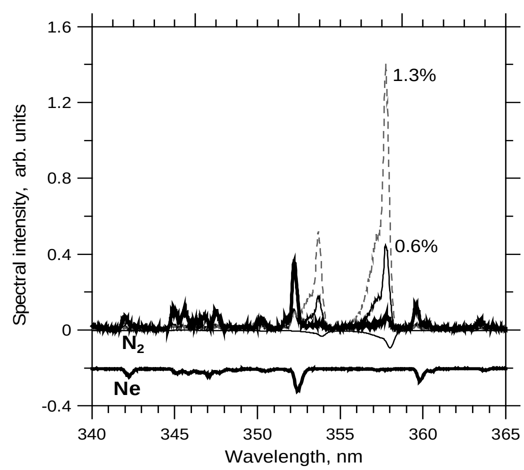


Fig. 6. Emissive spectra from the PK-4 plasma at $p = 50$ Pa of Ne and $I_{DC} = 3$ mA: for pure Ne (solid line); for Ne with 0.6% of air (thin line) and for Ne with 1.3% of air (dushed line) with the reference spectra of Ne and N_2.

proportional to the electron concentration n_e. For a control of the Ne purity, the ratio of the intensities 352.047 nm Ne / 357.69 nm N_2 has been chosen (Fig. 7). To keep the plasma parameter within the accuracy of about 20%, the neon purity should be not less than 0.999 in the PK-4 chamber. This corresponds to the ratio of the intensities 352.047 nm Ne / 357.69 nm N_2 of about 2 - 3.

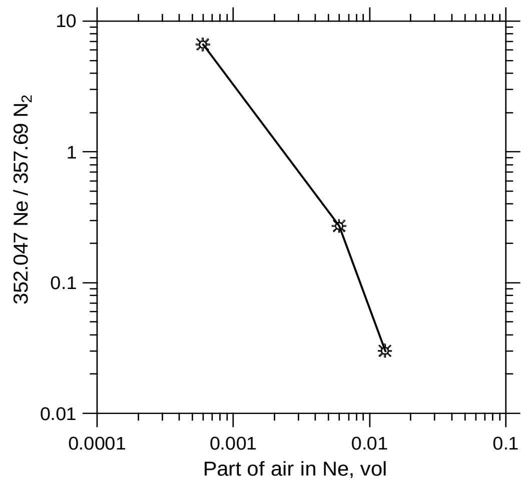


Fig. 7. The ratio of the intensities 352.047 nm Ne / 357.69 nm N_2 vs air concentration in Ne.

Fig. 8. The A-300 ZERO-G plane and the PK-4 experiment during the parabolic phase.

5 Preliminary results of dusty plasma experiments performed during parabolic flights from the Bordeaux Airbase (France, October 2003)

The parabolic flight campaign in October 2003 is a crucial step in the PK-4 Project (Fig. 8). The parabolic flights were performed on board of the A-300 ZERO-G plane of the NOVESPACE company [9]. The duration of the microgravity phase was about 20 seconds. As a rule, the campaign consists of 3 flight days with 30 parabolas per each day.

The main technical aims of this campaign were to check an operation of the PK-4 Setup as a whole under microgravity conditions, to refine the dispenser regimes, and to test the particle transportation from the dispenser to the area of the PK-4 experiments. During this parabolic campaign 4 dust injectors were installed and 4 sizes of the monodisperse polymeric spherical microparticles were used - 1.2, 3.4,

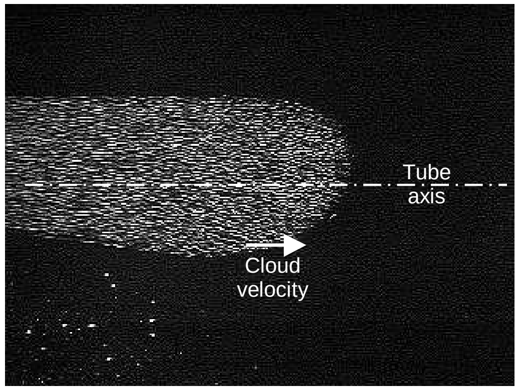


Fig. 9. Dust cloud in the pure dc discharge. Parameters of the experiment: $I_{DC} = 1$ mA, $p = 100$ Pa of Ne, dust grains with $d_p = 1.2$ μm, area shown is 21 × 16 mm^2.

6.8 and 11 μm. Here we present briefly the main scientific results achieved during the campaign without a detailed analysis.

5.1 Formation of the extended three-dimensional dust clouds in the positive column of the pure dc discharge

Whereas dust grains with a diameter smaller than 4 μm can be suspended under gravity, clouds with bigger grains can be immersed into a plasma only under microgravity condition. A typical shape of dust cloud in a pure dc discharge is presented in Fig. 9. The clouds are concentrated in the vicinity of the tube axis due to the electrostatic repulsion of the negatively charged dust grains from the negatively charged tube walls. The parameters of the created dust clouds are presented in Table 1. The simulation of the clouds is under developing.

Table 1. Mean intergrain distance D and dust grain density n_{p} in an extended 3D cloud vs dust grain size d_{p}

d_{p}, μm	D, μm	n_p, cm^{-3}
1.2	230	$2{\cdot}10^5$
6.8	370	$4{\cdot}10^4$
11	500	$1.3{\cdot}10^4$

5.2 Formation dust acoustic waves and solitons

Dust acoustic waves are a specific kind of dusty plasma instabilities [10]. Due to a large mass of the grains the wave frequency is about 10 Hz and the wave velocity is a few of cm/s. The PK-4 setup allows to reproduce this experiment in an extended uniform dust cloud (Fig. 10.a). Solitons or soliton-like waves appear in

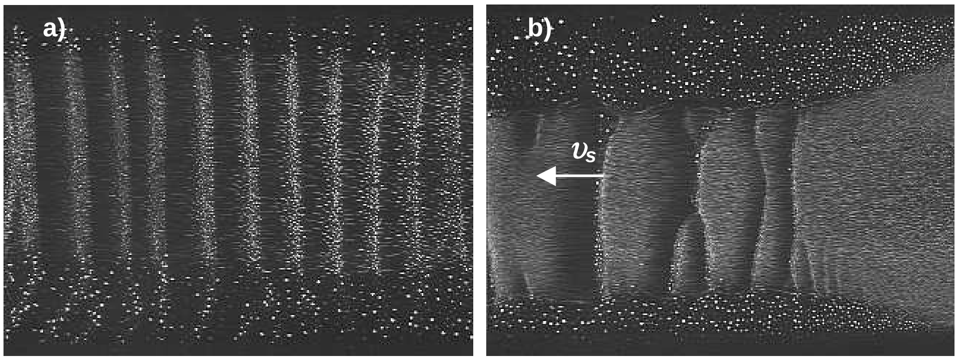


Fig. 10. Dust acoustic waves (a) and soliton-like waves (b) observed in the PK-4 complex plasma; u_s - direction of the soliton propagation.

the PK-4 dusty plasma (Fig. 10.b) near the high pressure limit of the dust-acoustic instability. Solitons could arise as result of long self-exiting waves or pulse action in the plasma. Such solitons consist of a gentle forward edge, where the dust particle concentration decreases, a section with a small dust particle concentration (and high electric field), and a sharp back edge with a short peak of the dust particle concentration. For an analysis of such waves the hydrodynamic approach can be used.

5.3 Structural and dynamical phenomena

During the campaign interesting structural and dynamical phenomena were observed in the experiments. In the pure rf mode the dust grains are confined in the rf glow in the field of ambipolar diffusion (Fig. 11.a). In case of the injection of particle mixtures into the PK-4 chamber, the grains are effectively separated by their size in the vicinity of the rf glow (Fig. 11.b) [11]. The flows of highly nonideal dust liquids exhibit specific features: sheared boundary layers and dust lane formation (Fig. 11.c). The jets of small particles can be used as a probe for electric field in the clouds of large particles (Fig. 11.d). The simulation of the phenomena is in progress.

6 Conclusion

During the predevelopment phase of the PK-4 Project the design of the setup with a combined dc/rf discharge was developed, the setup was constructed (in two units) and successfully tested as a whole during the parabolic flights under microgravity conditions. The basic parameters of the discharge plasma were measured in the lab. A convenient spectral criteria for controlling of the plasma impurities is proposed. A set of interesting dusty plasma phenomena was found during the parabolic flight test. simulations of the phenomena are currently developed.

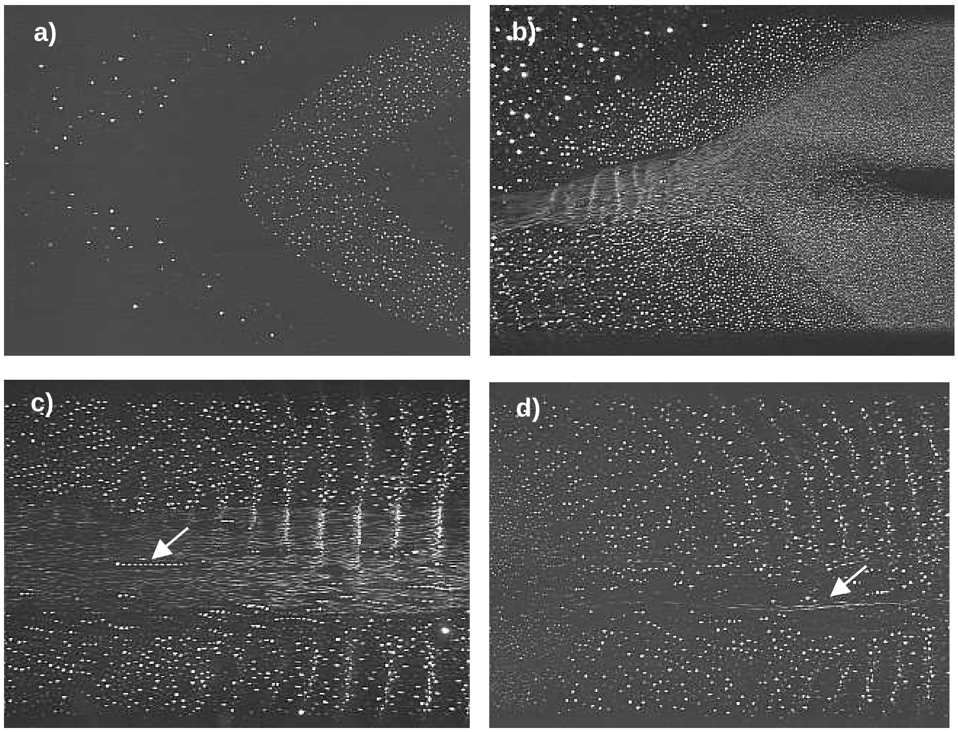


Fig. 11. Structural and dynamical phenomena in the PK-4 setup: a) dust ordering around the rf inductive glow; b) spatial separation of dust grains by their size in the rf glow; c) particle line formation in a dust flow; d) dust jet.

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References

[1] J. H. Chu and I. Lin: Phys. Rev. Lett. textbf72 (1994) 4009.

[2] H. M. Thomas, G. E. Morfill, *et al*: Phys. Rev. Let. **73** (1994) 652.

[3] H. M. Thomas and G. E. Morfill, Nature (London) **379** (1996) 806.

[4] A. P. Nefedov, O.F. Petrov, V. E. Fortov: Physics-Uspekhi **40** (1997) 1163.

[5] http://www.mpe.mpg.de/www_th/plasma-crystal/PK4/index.html.

[6] V. E. Fortov *et al.* JETP, **87**, (1998) 1087.

[7] A. P. Nefedov, O. F. Petrov, V. E. Fortov *et al*: New J. Phys. **5** (2003) 33.1.

[8] http://www.mpe.mpg.de/www_th/plasma-crystal/PK4/gal06a.html.

[9] http://www.novespace.fr/

[10] V. E. Fortov, A. D. Usachev, A. V. Zobnin, *et al*, Phys. Plasmas **10** (2003) 1199.

[11] A. V. Zobnin, A. D. Usachev, V. E. Fortov: *Dusty Plasmas in the New Millenium. Proceedings of the Third International Conference on the Physics of Dusty Plasma, Durban, South Africa, 20-24 May 2002* (Eds. P. Bharuthram, *et al*) AIP, New York, 2002, 293.