Recent results from the PK-4 experiments with dusty plasmas under microgravity conditions

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Outline:

1. Introduction into the PK-4 Project

2. Recent results from the PK-4 experiments under microgravity:
   • Electrical manipulative (EM) electrode technology for manipulation of dusty plasmas
   • Micro-rods in DC discharge
   • The formation of a boundary-free dust cluster due to attractive forces caused by ion fluxes in a bulk plasma region
1. Introduction into the PK-4 Project

2002-2006: Predevelopment Phase
2006-2007: Preliminary Design Review (Phase A/B)
2008-2009: Phase Gate Review (Phase C/D)

Involved Partners:

Concept, science, engineering

Space Agencies:

Industry:
Scheme of the PK-4 experiment:

Main experimental parameters:

- Discharge gas: Ne, Ar, Ne+CF₄; Ne+O₂
- Discharge gas pressure: 2 – 266 Pa
- DC: 0.2 – 3 mA
- PS-DC mode: 1 kHz
- RF(i) power < 5 W
- Dust particles: 1 – 12 mcm
- Gas flow 0.2 – 12 sccm
PKE-4 is a soon coming space experiment:

- UV-induced dusty plasma
- Combined DC/RF(i)/EM dusty plasma
- DC dusty plasma
- RF(e) dusty plasma
- Combined DC/RF(i)/EM dusty plasma

Experiments:
- PK-2 (2000): RF(e) dusty plasma
- PK-3 Nefedov (2006): RF dusty plasma
- PK-3 Plus (2011): RF dusty plasma
- PK-4 (2013): Combined DC/RF(i)/EM dusty plasma
- PK-5 (2013):
PK-4 setup at the JIHT RAS:
PK-4 setup at the MPE:

Dust injectors:

EM electrode:

TM element:
PK-4 setup for Parabolic Flight Experiments (MPE):
Designed PK-4 setup for the ISS:
Why microgravity?

PK – 3; PK – 3 Plus

PK – 4

$g = 1$

$g = 0$

$g = 1$

$g = 0.04$
2003÷2008 = 5 PK-4 PF JIHT Campaigns with the MPE:

- 2003 (ESA)
- 2004 (DLR)
- 2006 (ESA)
- 2007 (DLR)
- 2008 (ESA)
22 seconds of microgravity ...
2.1. Electrical manipulative (EM) electrode technology for manipulation of dusty plasmas

1. By a pulse of the RF(i) discharge:

2. By an EM electrode:
   - Negative pulse $V$, $I = 0.6$ mA

3. Ideally, by a Mesh electrode (in PF):
Influence of Negatively biased EM-electrodes on DC discharge
Influence of Negatively biased EM-electrodes on dusty cloud in lab

DC discharge mode, constant negative bias

Cathode

Anode
Influence of Negatively biased EM-electrodes on dusty cloud under microgravity

DC discharge mode, constant negative bias

$I_{EM} = 0.1 \text{ mA (-200V)}$

$I_{EM} = 0.2 \text{ mA (-300V)}$
Influence of Negatively biased EM-electrodes on dusty cloud under microgravity

DC discharge mode, pulse negative bias
Influence of Negatively biased EM-electrodes on dusty cloud under microgravity

PS(1 kHz)-DC discharge mode, pulse negative bias
2.2. Micro-rods in DC discharge

**Motivation:**

1. Utilization of micro-rods instead of spherical microparticles permits one sufficiently extend possible states of dusty plasmas.

2. Investigation of physics of orientational ordering, orientational waves, orientational instabilities, etc.

3. Micro-rods are sensitive contact-less tool for diagnostics of permanent electric fields in low temperature.

Unique mono-disperse micro-rods from prof. K. Yoshino, Osaka, Japan

D=10 mkm, L=300 mkm

Micro-rod mass $>>$ Micro-sphere mass
Scheme of the experiment with micro-rods in DC-discharge under microgravity

Time diagram of the experiments
Micro-rods ordering in DC discharge

$\text{Ne, } p=25, 35, 50 \text{ Pa, } I=1 \text{ mA}$

Image size: $21\text{mm} \times 17\text{mm}$
Comparison of two “rod DC dusty plasmas”

Nefedov, Molotkov et al, 2000

- Tube diameter: 3 cm.
- Discharge current: 3.8 mA.
- Rods: L=300 mkm; D=10 mkm.
- Neon pressure: 50 Pa.
- Mean inter-rod distance: 1.3 mm.

Present work, 2008

- Tube diameter: 3 cm.
- Discharge current: 1 mA.
- Rods: L=300 mkm; D=15 mkm.
- Neon pressure: 120 Pa.
- Mean inter-rod distance: 0.4 mm.
Contact-less diagnostics of permanent electric fields in plasmas

Radial ambipolar field $E_R$ – is diagnosed

$E_R = E_0 \cdot \tan \alpha$

Longitudinal discharge field

$E_0 = 2.1 \text{ V/cm}$

Radial electric field strength

Schottky’s theory

Falling spherical particles

Rod diagnostics

Probe diagnostics

Tube axis

11 mm x 9 mm

13th PNP Conference, Chernogolovka, September 13 – 18, 2009
Dust acoustic instability in rod dusty plasma at 25 Pa

\( P = 25 \text{ Pa} \)
\( N_R \sim 8000 \text{ cm}^{-3} \),
\( \nu \sim 0.4 \pm 0.1 \text{ Hz} \),
\( \lambda \sim 1.1 \pm 0.4 \text{ cm} \),
\( C_{DAW} \sim 0.5 \text{ cm/sec} \)

21 mm × 17 mm
Estimation of the rod charge using the “low-frequency” limit of linearized DAW equation:

\[
\frac{\omega}{k} = u_0 \frac{\omega_{pd}^2}{\omega_{pi}^2} \frac{v_{i}^{\text{eff}}}{v_{dn}} = C_{DAW}
\]

\[
Z_{MC} e E_0 = m_{MC} v_{dn} u_{MC} \quad \quad e E_0 = m_i u_0 v_{i}^{\text{eff}}
\]

\[
C_{DAW} = \frac{Z_{MC} n_{MC}}{n_i} u_{MC}
\]

where

\[u_0\] – ion drift velocity in \(E_0\); \(u_{MC}\) – micro-cylinder drift velocity in \(E_0\)

\[Z_{MC} = 85000 - 170000 \ e\]
2.3. Experimental investigation of boundary-free dusty plasma structures:

Plasma flux pressure > Electrostatic repulsion

Main conditions for formation of boundary-free dusty-plasma structures:

1. Plasma recombination rate on dust particles. $F_i > F_e$; $n_e > 10^9$ cm$^{-3}$.

2. Plasmas recombination rate on dust particles.

3. Condition for collective interaction

$F_i > F_e$; $n_e > 10^9$ cm$^{-3}$.

$r_D^2 / r_p^2 << T_e / T_i \sim 100$

$r_p \gg 2$ mcm.
1. Under gravity boundary-free structures are not possible.

2. Dust cloud should be situated in central region of discharge chamber.
Experimental configuration of the PK-4 Setup

1. Gas: Neon
2. Pressure: 60 Па
3. DC: 1 мА
4. RF(i) power: 1.5 W
Experimental parameters:

Preliminary DC mode:

\[ n_i, n_e = 2 \cdot 10^8 \text{ cm}^{-3} \]
\[ T_e = 7 \text{ eV} \]

Active RF mode:

\( \tau = 180 \text{ ms} \)

\[ n_i, n_e = 4 \cdot 10^9 \text{ cm}^{-3} \]
\[ T_e = 3.5 \text{ eV} \]
Formation of a Boundary-Free Dust Cluster (slow down in 12 times)

Image size: 21mm×17mm
Formation of a Boundary-Free Dust Cluster (slow down in 60 times)

Image size: 7mm×3mm
Scheme of the Boundary-Free Dust Cluster

\[ \lambda_{Di} \approx 19 \, \mu m; \quad \lambda_{in} \approx 80 \, \mu m; \quad R_{cl} = 190 \, \mu m \]
Equilibrium condition for small particle at \( r = R_{cl} \):

\[
|F_i(R_{cl})| = |F_e(R_{cl})|
\]

\[
|F_{id}| = \left(2\sqrt{2}/3\right) m_i n_i u_i \nu_{T_i} r_{p2}^2 z_{p2}^2 \tau^2 \Lambda_{id}
\]

\[
\Lambda_{id} = 2z \int_0^\infty e^{-2x} \ln[1 + 2\tau^{-1}(\lambda_{D_i} / r_{p2})x]dx
\]

\[
z_{p2} = |Z_{p2}| e^2 / (4\pi\varepsilon_0 r_{p2} T_e)
\]

\[
F_{id}(R_{cl}) = 3.3 \cdot 10^{-14} \text{ N}
\]

Electrostatic potential around the big particle calculated in different approximations:

1 – Debye-Hückel potentials with the linearized ion Debye length \( r_{D_i} = 19 \mu\text{m} \);

2 – unscreened potential = \( eZ_{p1} r_{p1} / 8\pi\varepsilon_0 r^2 \) due to the OML ion current on the big particle in the collisionless regime;

3 – \( \varphi = 3.2 \cdot 10^{-6} (\text{V}\cdot\text{m})/r \) which supports ion current to the big particle in the mobility regime;

4 – self consistent numerical calculation
Conclusion:

Microgravity conditions is quite necessary for successful dusty plasma experiments!
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