13th International Conference on Physics of Non-Ideal Plasmas
Chernogolovka, September 13 – 18, 2009

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

A. Usachev, A. Zobnin, O. Petrov, and V.E. Fortov
Joint Institute for High Temperatures of RAS, 125412 Moscow, Russia

M. Thoma, H. Höfner, M. Kretschmer, M. Fink, and G. E. Morfill
Max-Planck-Institut für extraterrestrische Physik, D- 85740 Garching, Germany

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)

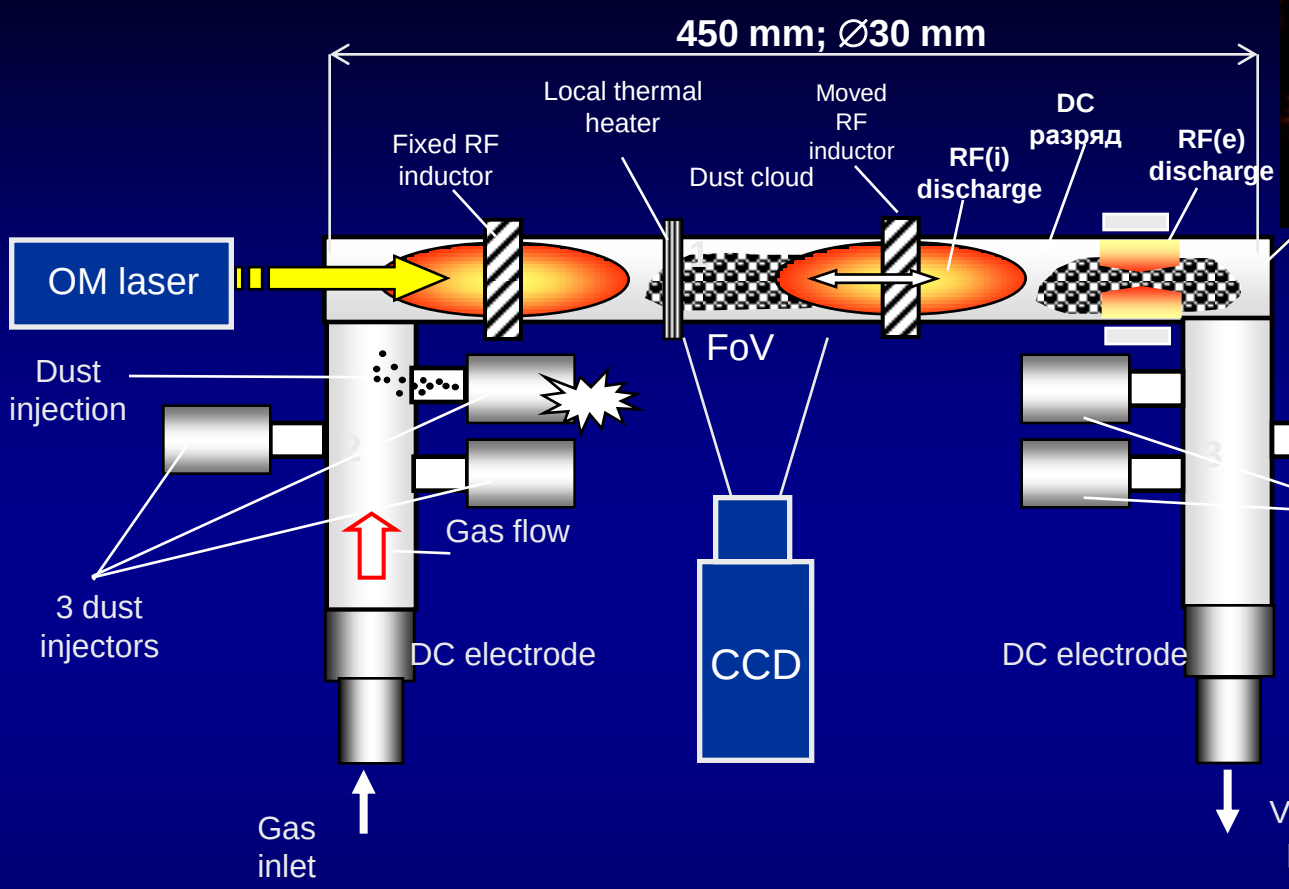
Involved Partners:

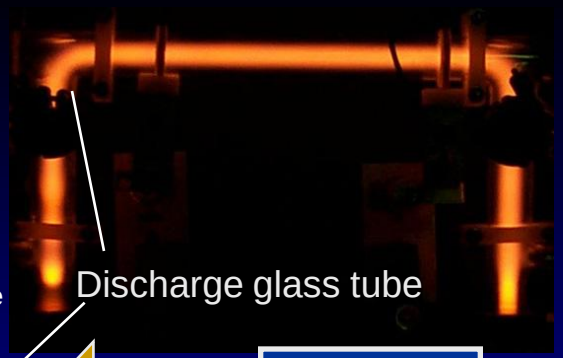
Concept, science, engineering

Space Agencies:

Industry:

Scheme of the PK-4 experiment:

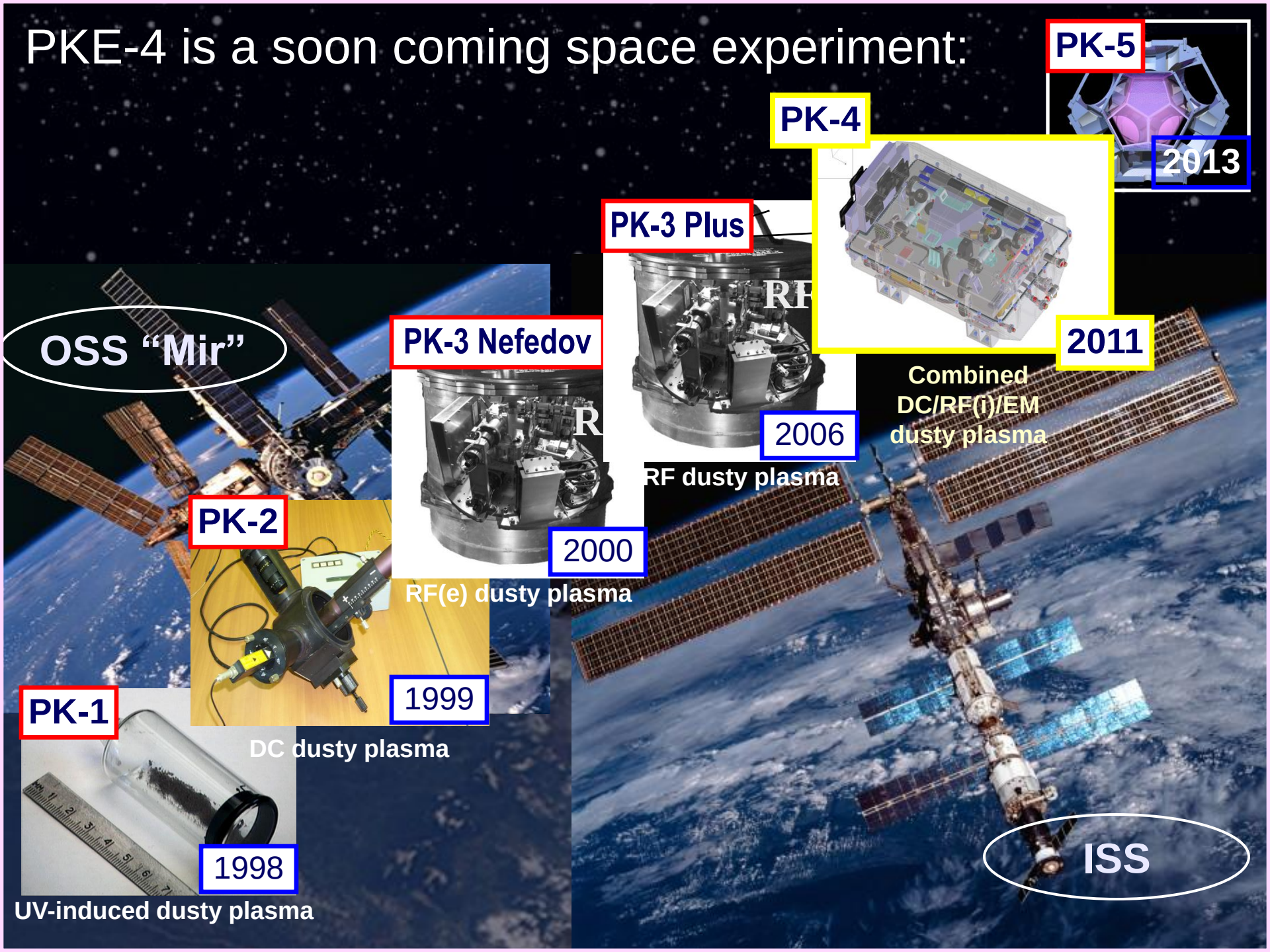




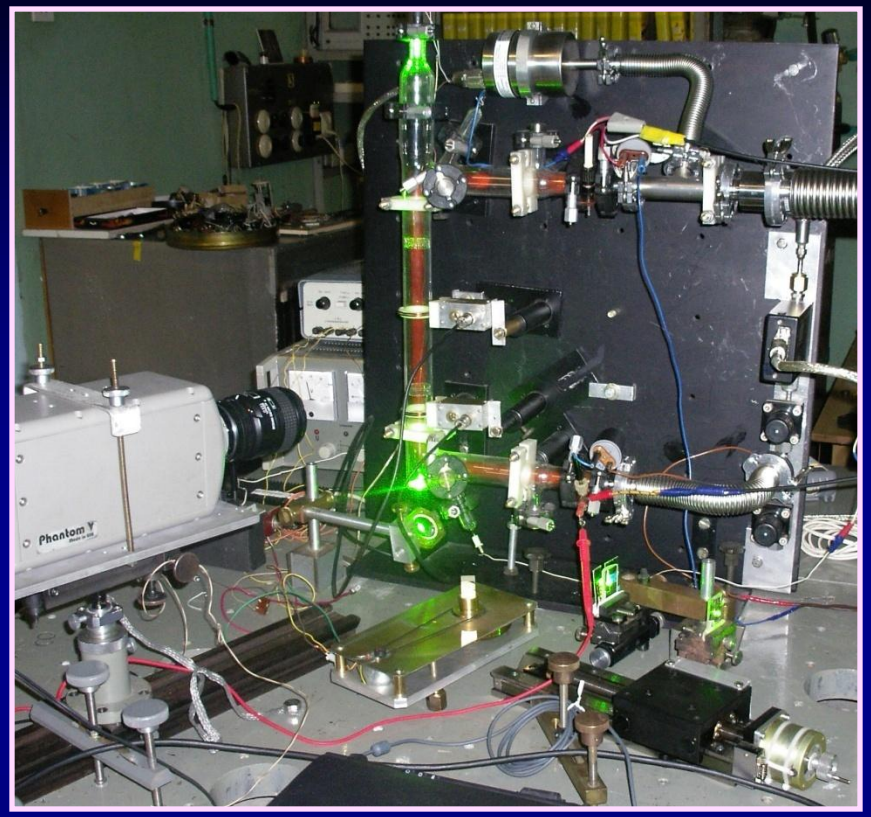
Main experimental parameters:

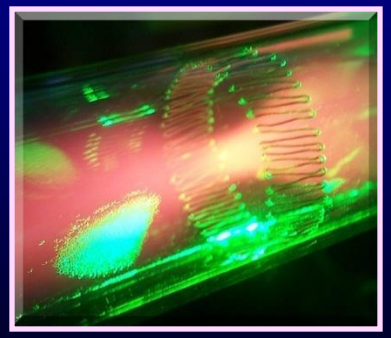
- Discharge gas: Ne, Ar, Ne+CF_4; Ne+O_2
- Discharge gas pressure: 2 – 266 Pa
- DC: 0,2 – 3 мА
- PS-DC mode: 1 kHz
- RF(i) power < 5 W
- Dust particles: 1 – 12 mcm
- Gas flow0.2 – 12 sccm

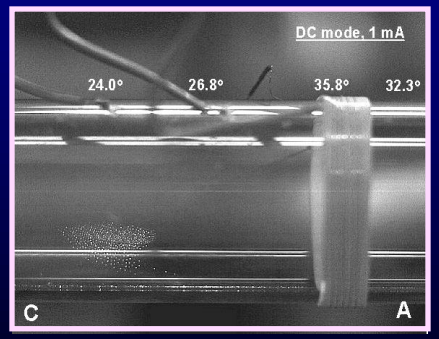
PKE-4 is a soon coming space experiment:

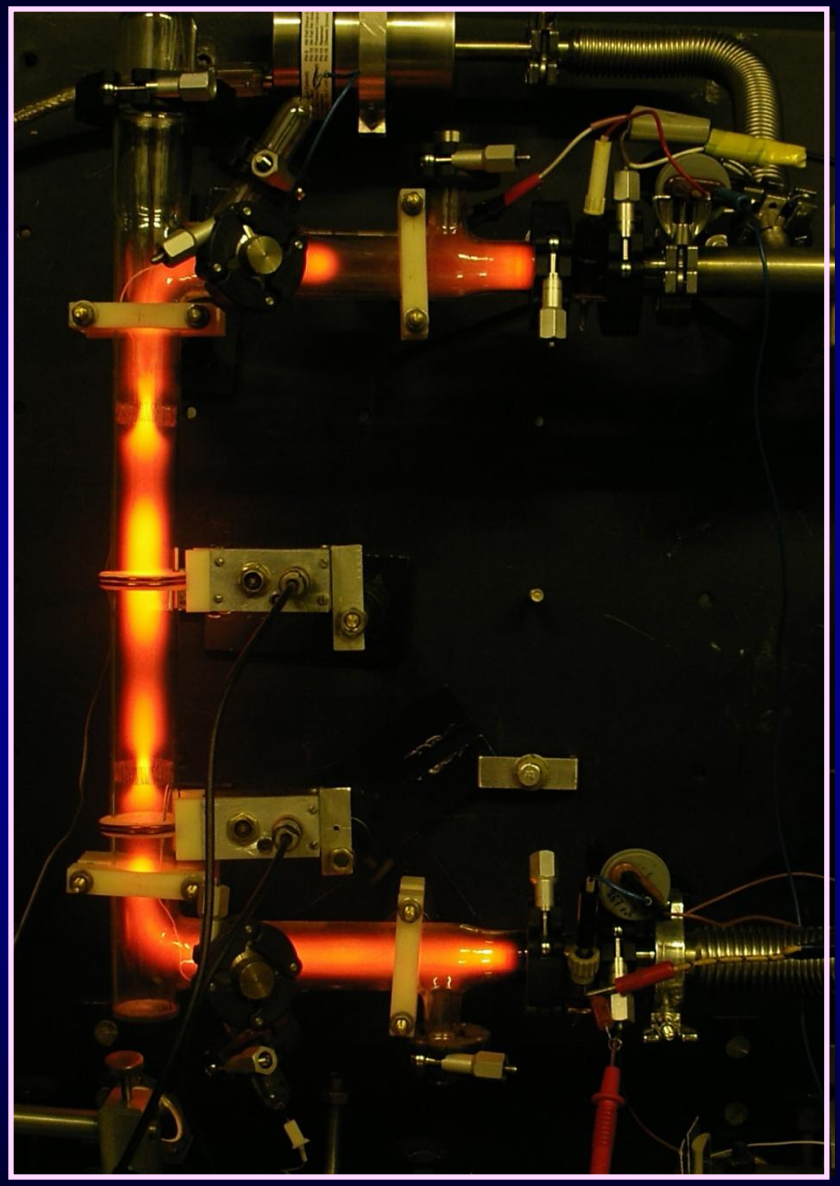


PK-4 setup at the JIHT RAS:

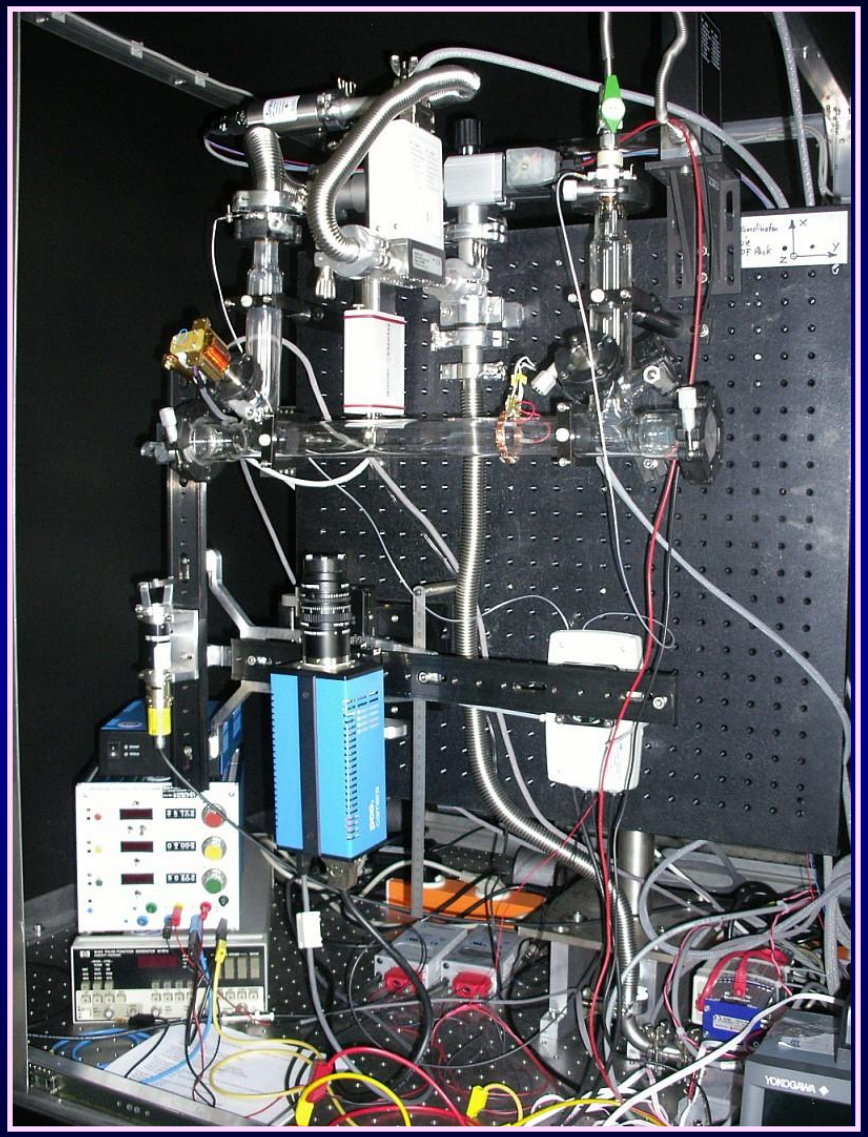


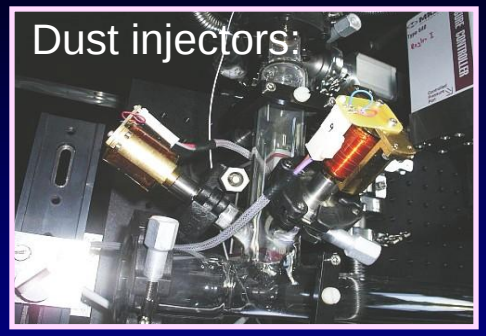


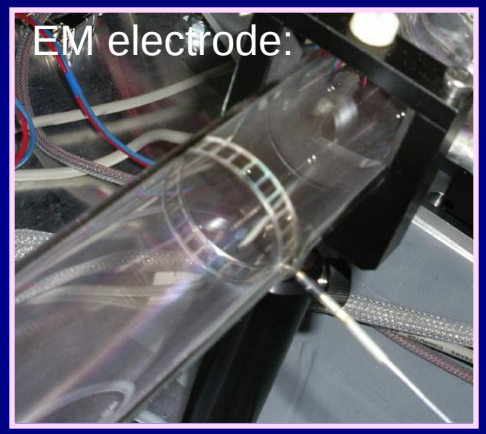


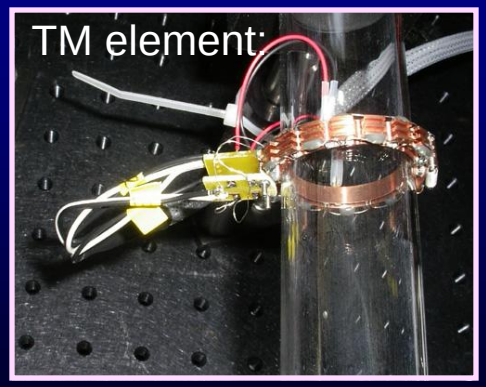


PK-4 setup at the MPE:

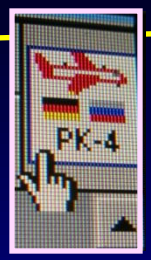


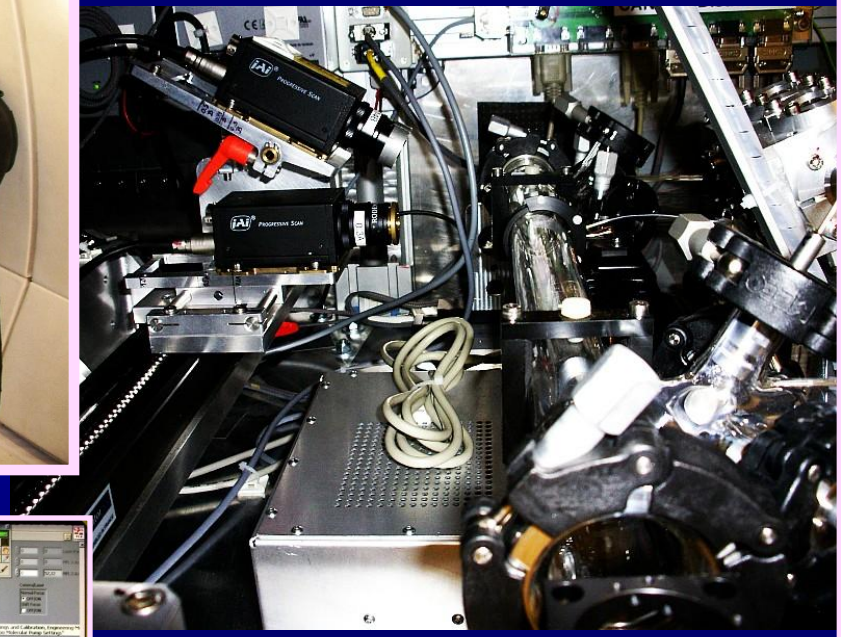


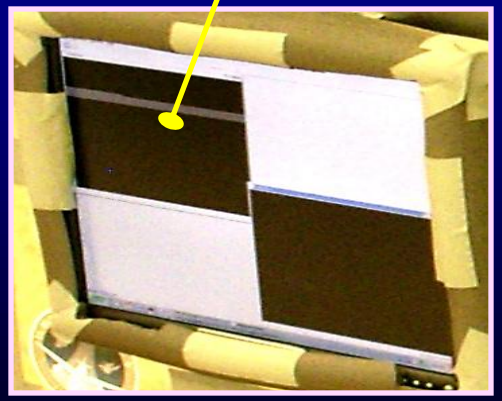


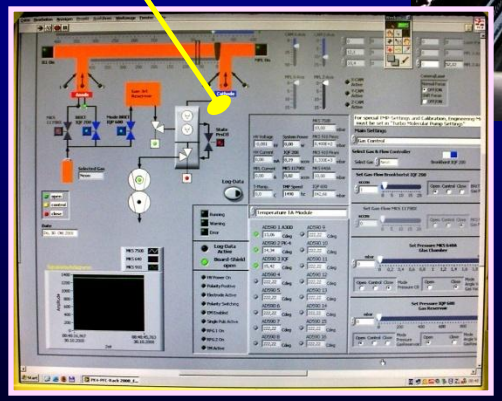


PK-4 setup for Parabolic Flight Experiments (MPE):

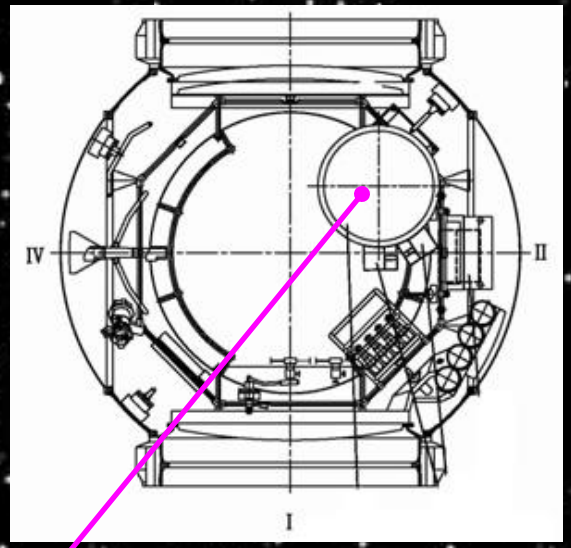


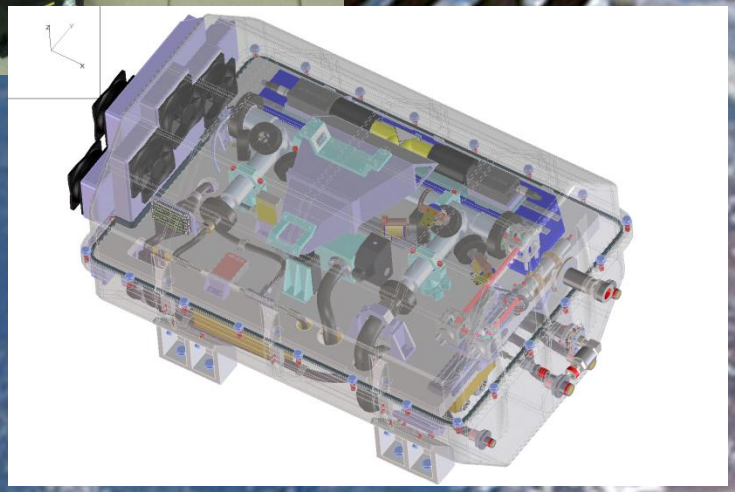






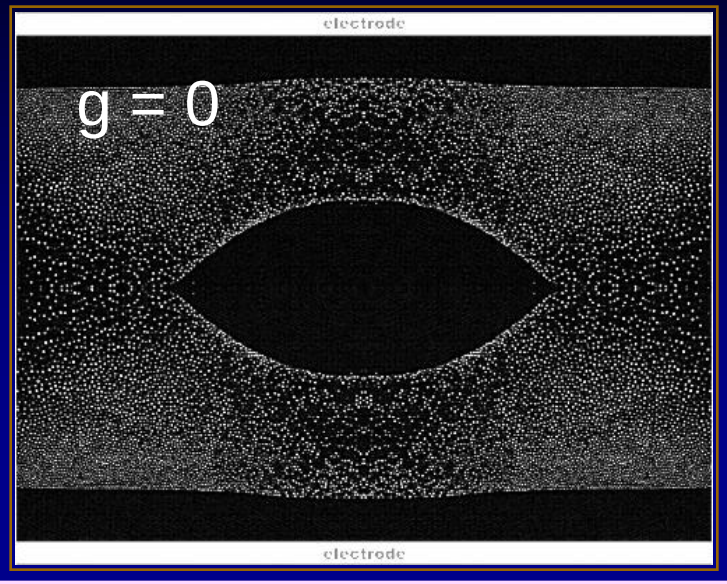
Designed PK-4 setup for the ISS:



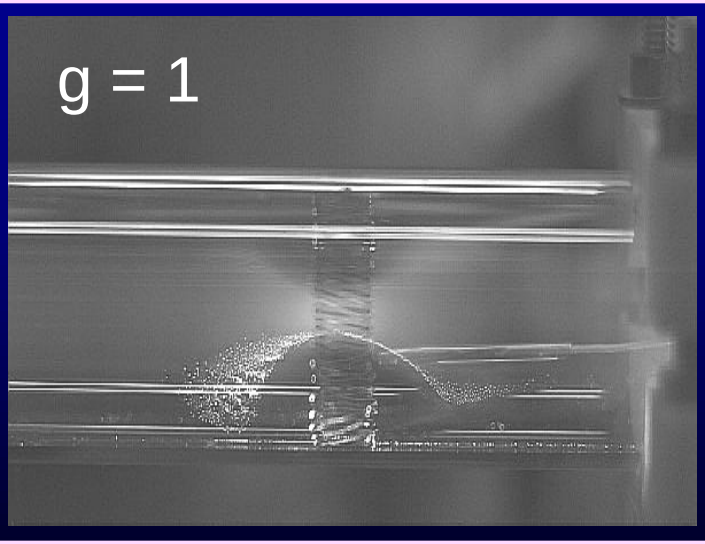


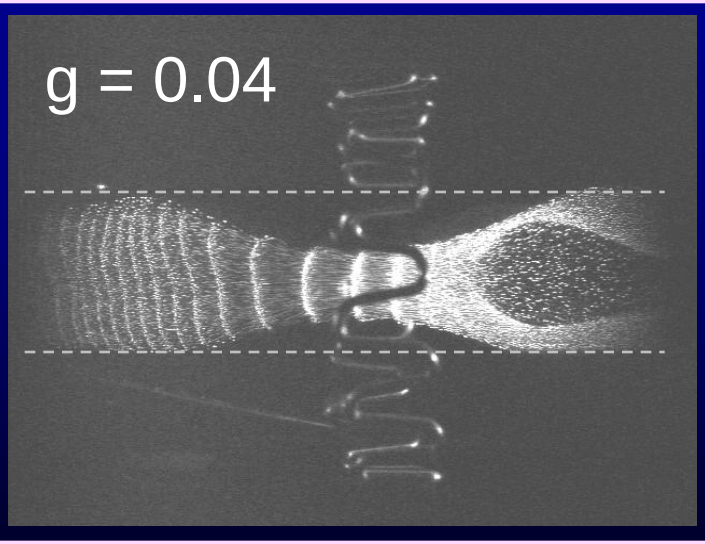
Why microgravity?

PK – 3;
PK – 3 Plus



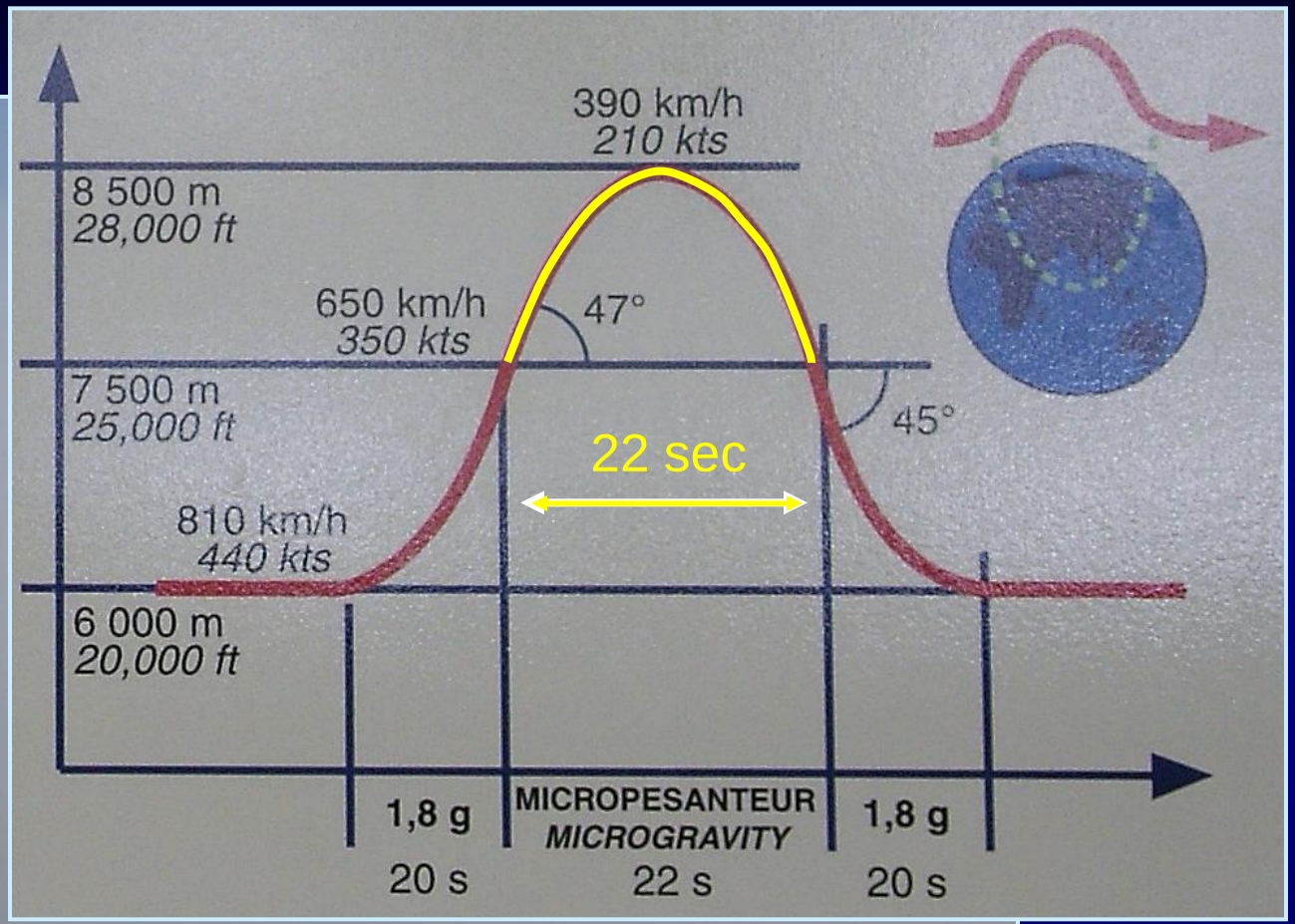
PK – 4

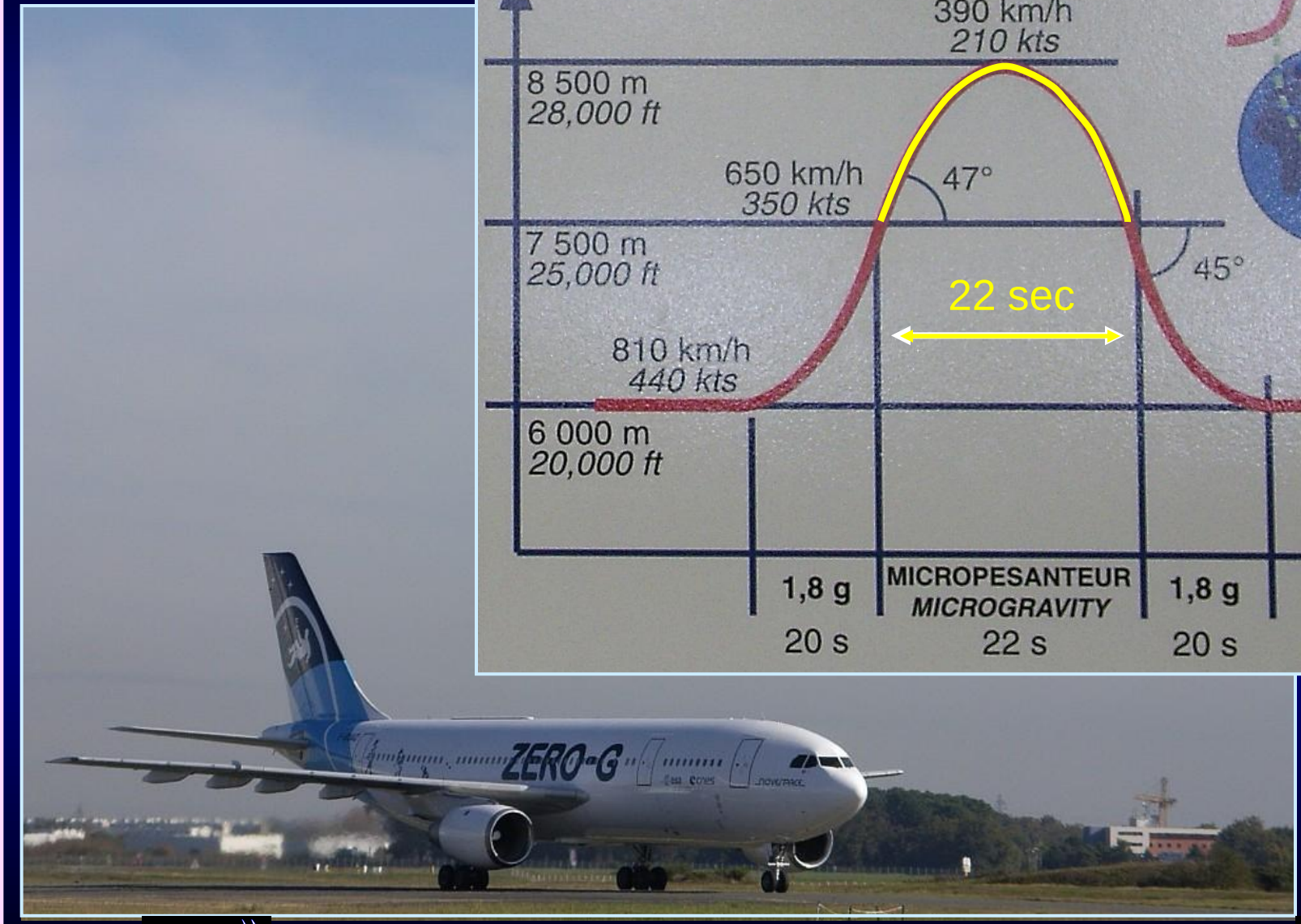




2003÷2008 = 5 PK-4 PF JIHT Campaigns with the MPE:

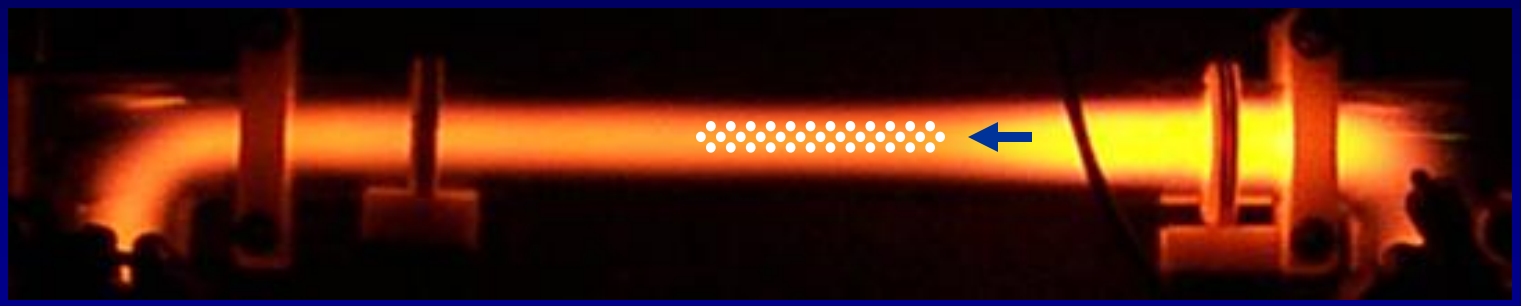
22 seconds of microgravity …



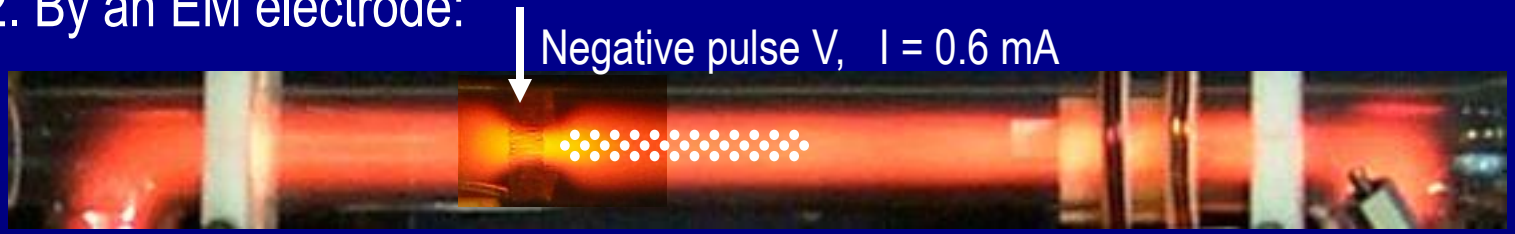


2.1. Electrical manipulative (EM) electrode technology for manipulation of dusty plasmas

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

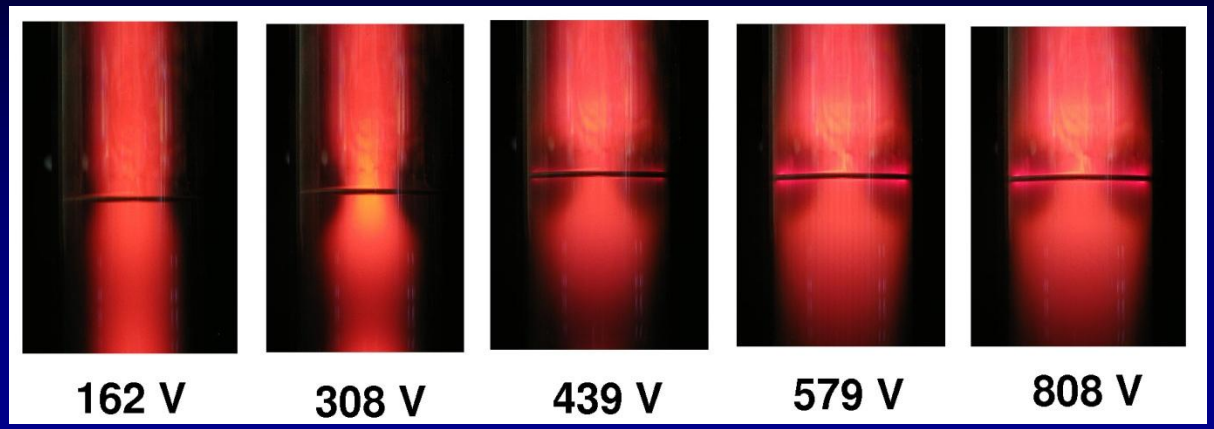


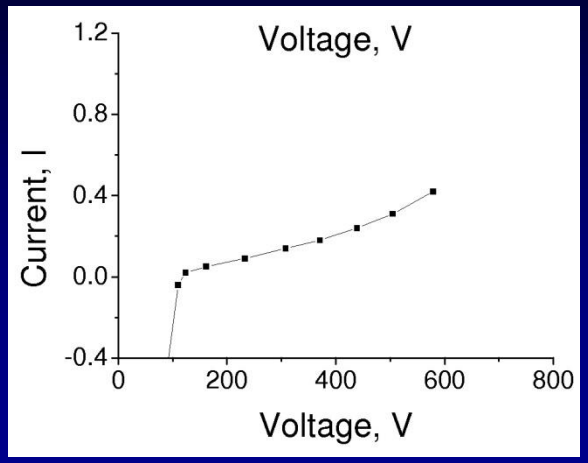
2. By an EM electrode:

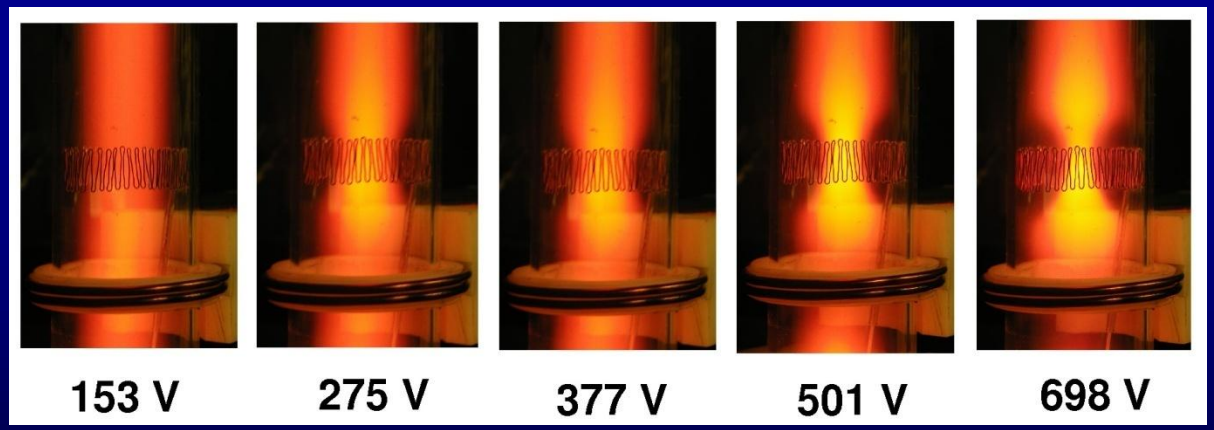


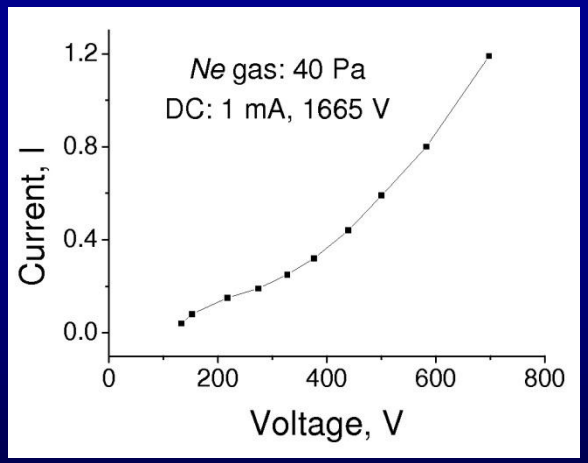
3. Ideally, by a Mesh electrode (in PF):

Influence of Negatively biased EM-electrodes on DC discharge



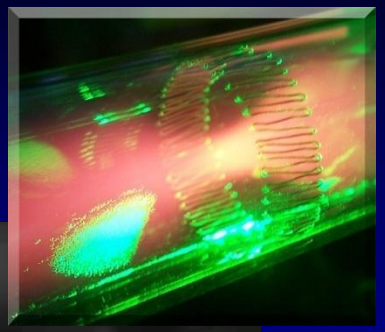






Influence of Negatively biased EM-electrodes on dusty cloud in lab

DC discharge mode, constant negative bias

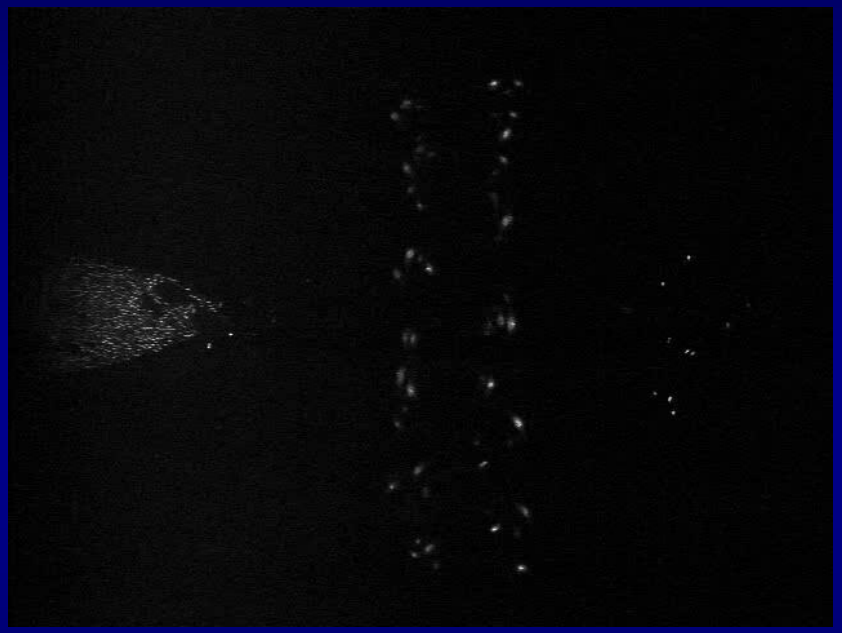


Cathode

Anode

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

DC discharge mode, constant negative bias

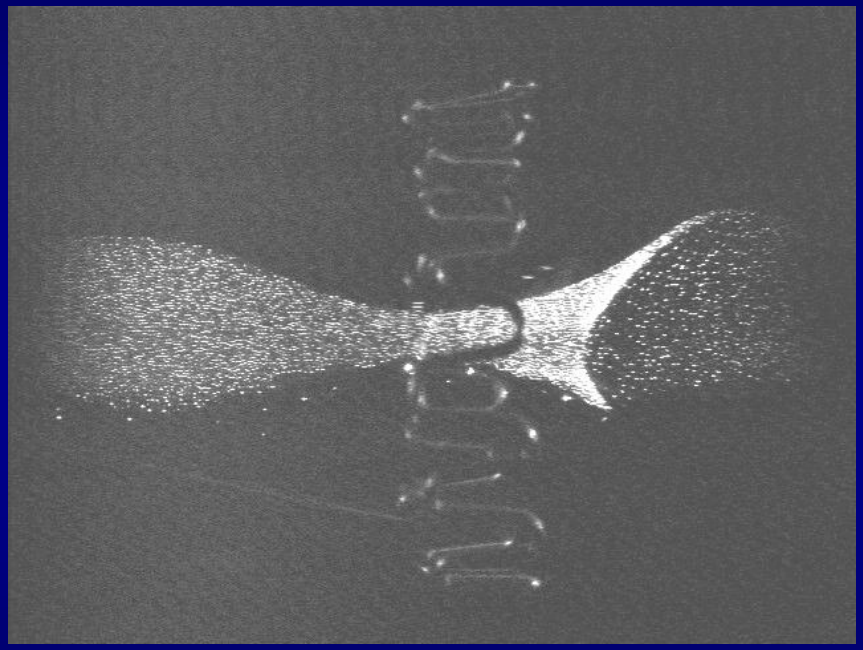


I_{EM} = 0.1 mA (-200V)

I_{EM} = 0.2 mA (-300V)

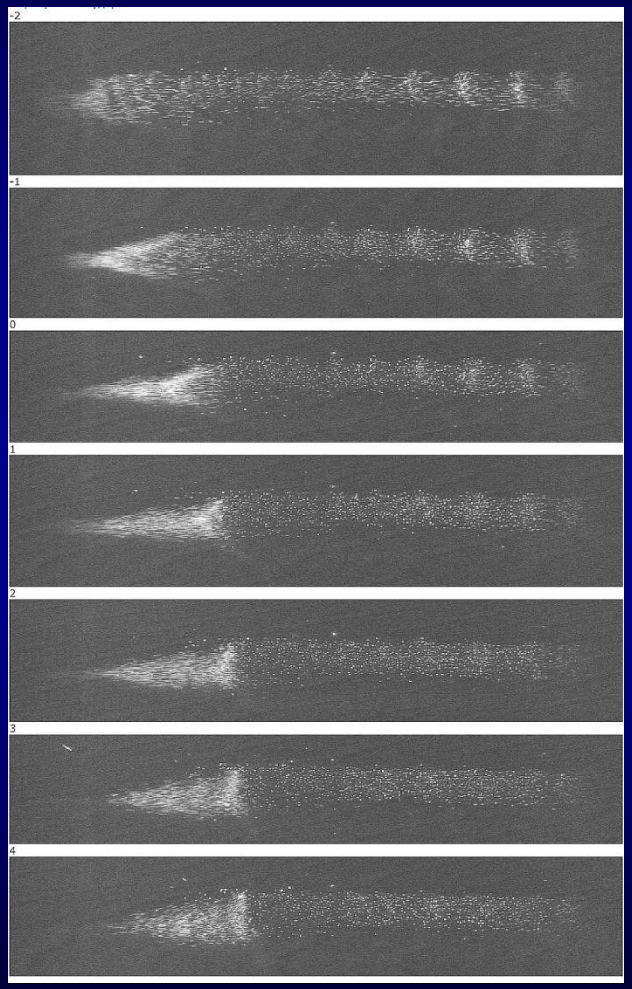
Influence of Negatively biased EM-electrodes on dusty cloud *under microgravity*

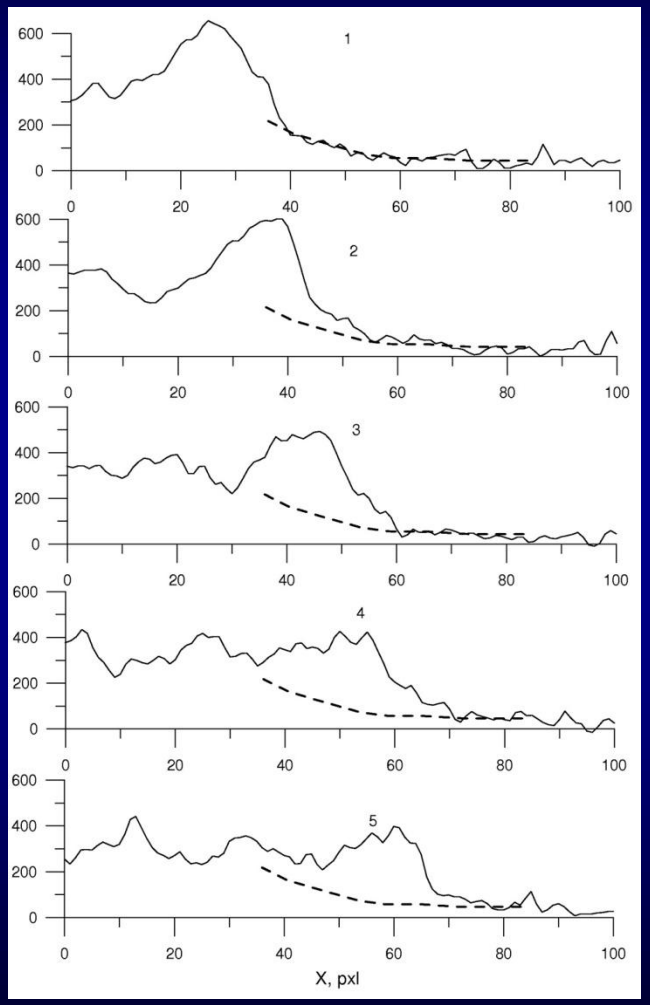
DC discharge mode, pulse negative bias



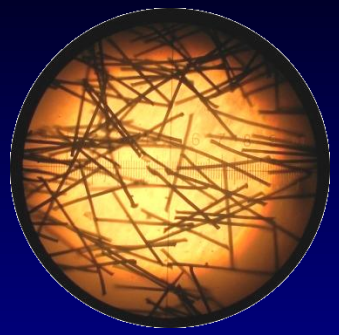
Influence of Negatively biased EM-electrodes on dusty cloud *under microgravity*

PS(1 kHz)-DC discharge mode, pulse negative bias



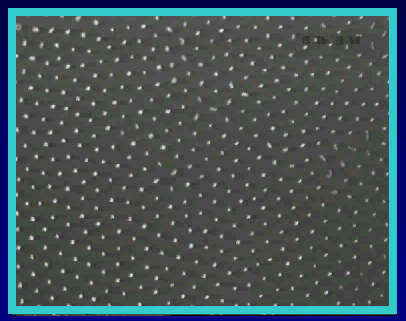


2.2. Micro-rods in DC discharge



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

D=10 mkm, L=300 mkm

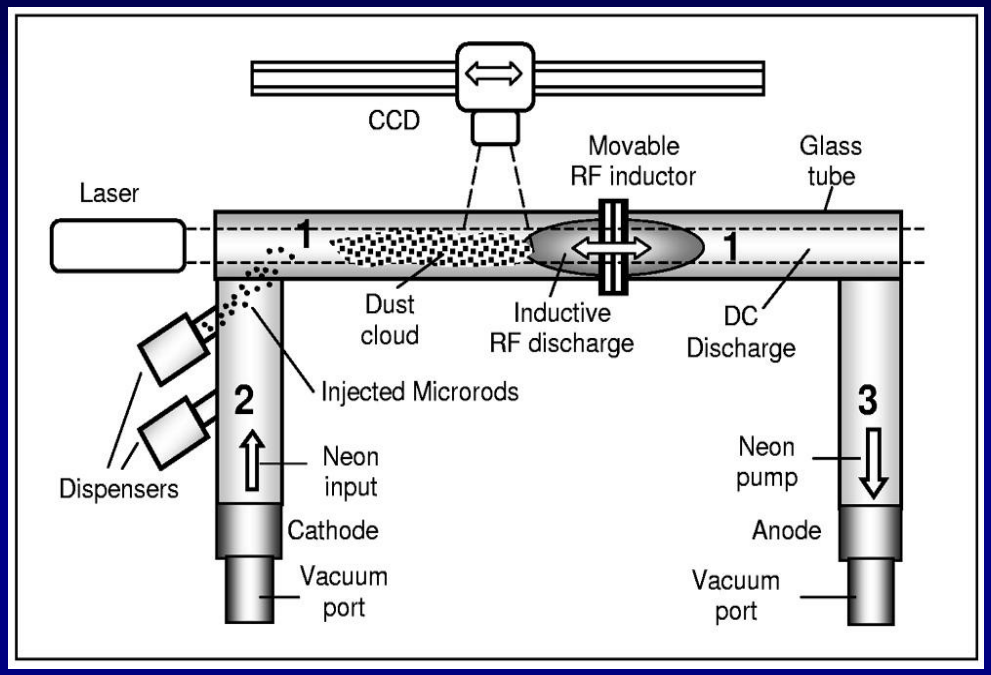


Micro-rod mass >> Micro-sphere mass

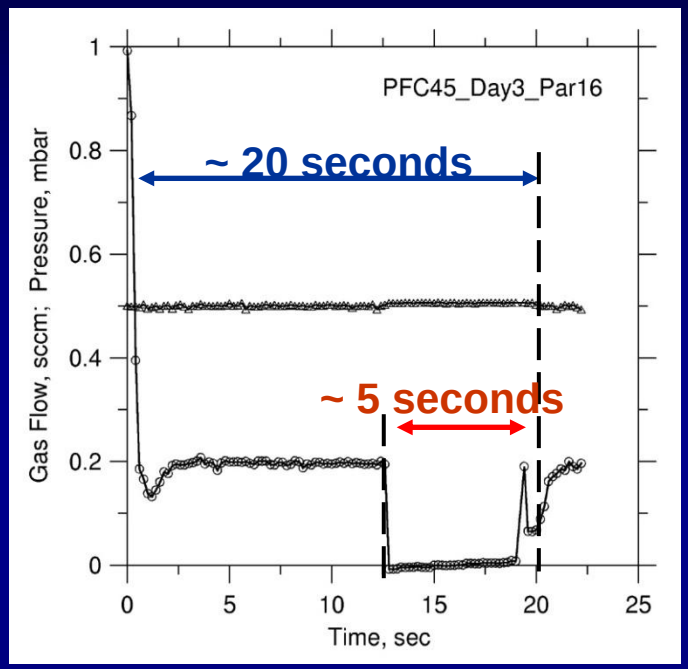
Motivation:

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.

Scheme of the experiment with micro-rods in DC-discharge *under microgravity*



Time diagram of the experiments



Micro-rods ordering in DC discharge

Ne, p=25, 35, 50 Pa, I=1 mA

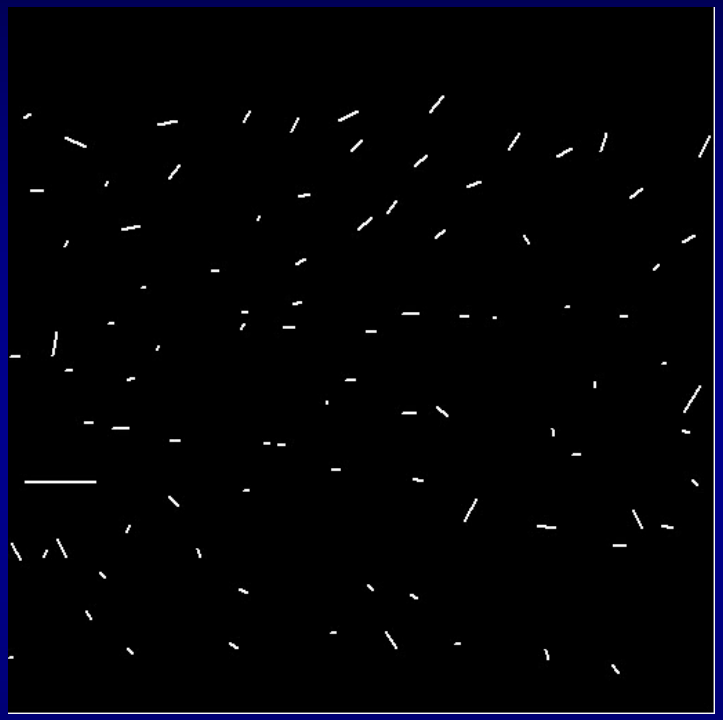


Image size: 21mm×17mm

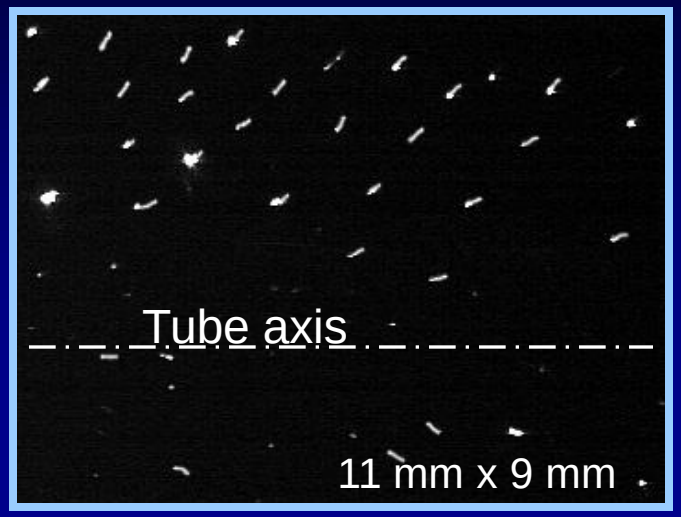
Comparison of two “rod DC dusty plasmas”

Nefedov, Molotkov et al, 2000

Tube cross-section

- Tube diameter: 3 cm.
- Discharge current: 3.8 mA.
- Rods: L=300 mkm; D=15 mkm.
- Neon pressure: 120 Pa.
- Mean inter-rod distance: 0.4 mm.

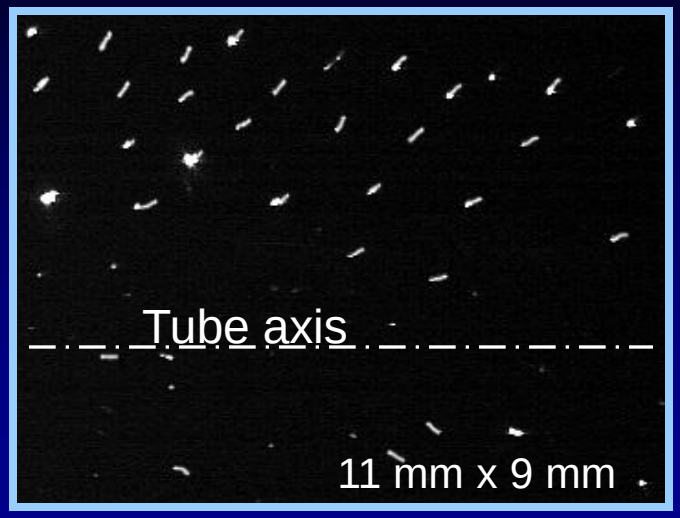
Present work, 2008



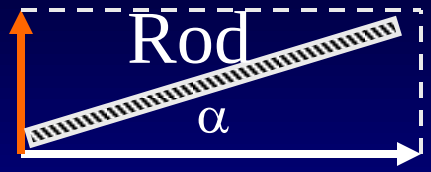
Tube longitudinal section

- Tube diameter: 3 cm.
- Discharge current: 1 mA.
- Rods: L=300 mkm; D=10 mkm.
- Neon pressure: 50 Pa.
- Mean inter-rod distance: 1.3 mm.

Contact-less diagnostics of permanent electric fields in plasmas



Radial ambipolar field E_R – is diagnosed

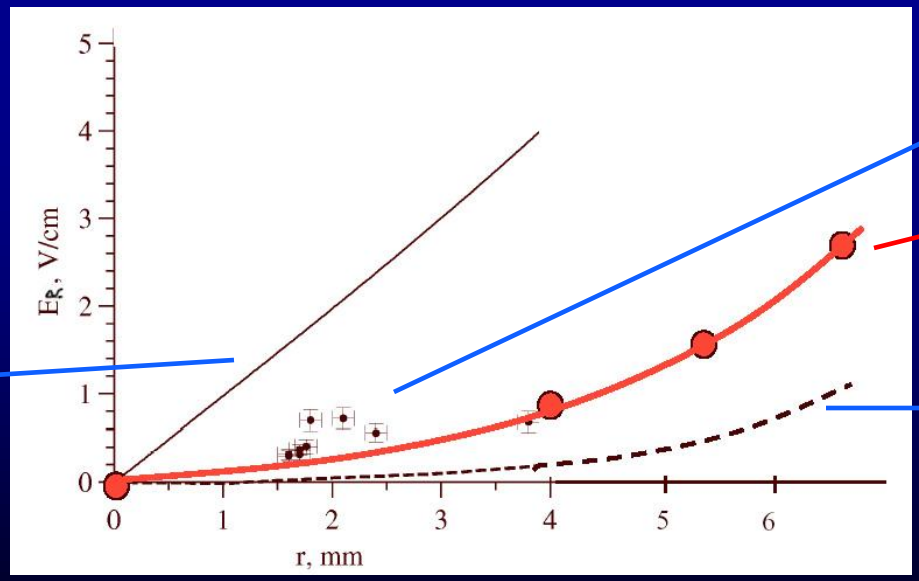


$E_R = E_0 \operatorname{tg} \alpha$

Longitudinal discharge field $E_0 = 2.1$ V/cm

Radial electric field strength

Schottky's theory

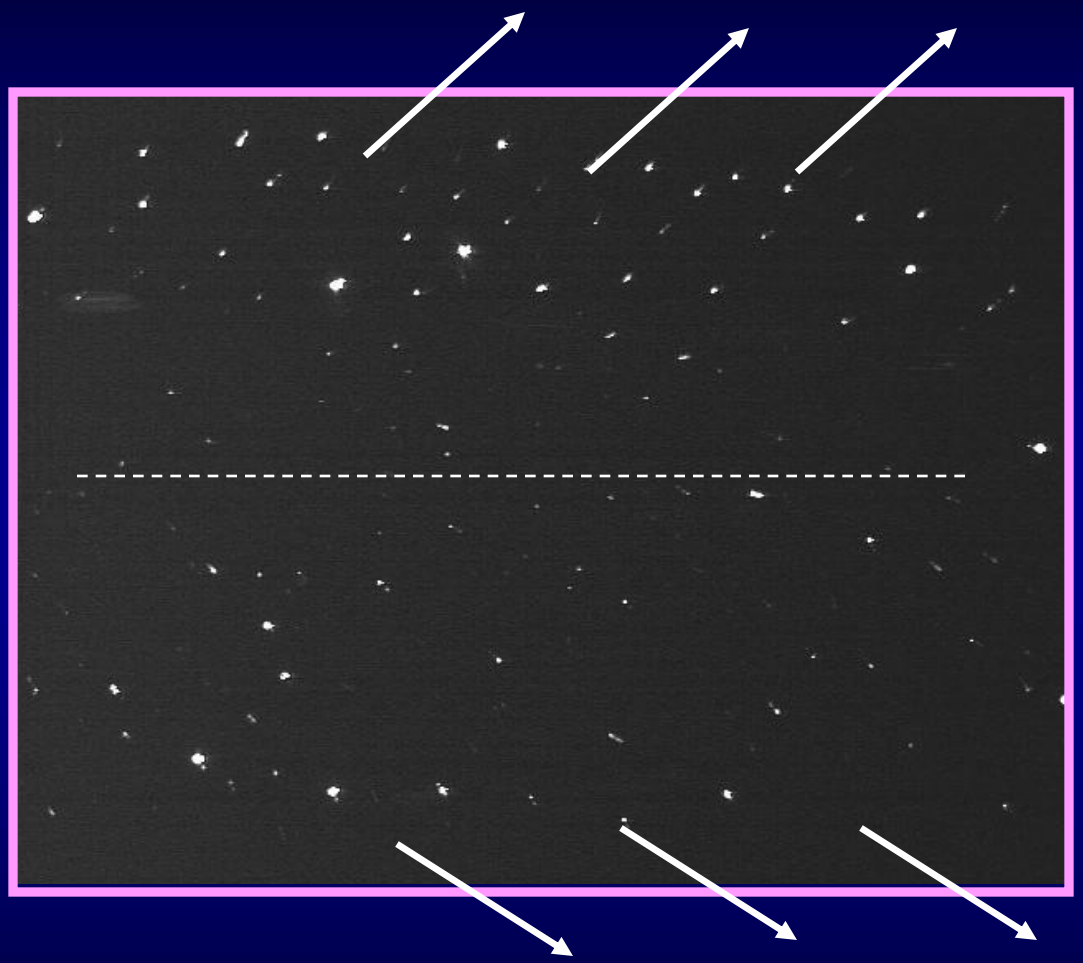


Falling spherical particles

Rod diagnostics

Probe diagnostics

Dust acoustic instability in rod dusty plasma at 25 Pa



21 mm ×17 mm

P = 25 Pa

N_R ~ 8000 cm^{-3},

ν ~ 0.4±0.1 Hz,

λ ~ 1.1±0.4 cm,

C_{DAW} ~ 0.5 cm/sec

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

$$\frac{\omega}{k} = u_0 \frac{\omega_{pd}^2}{\omega_{pi}^2} \frac{v_i^{eff}}{v_{dn}} = C_{DAW}$$

$$Z_{MC} e E_0 = m_{MC} v_{dn} u_{MC} \qquad e E_0 = m_i u_0 v_i^{eff}$$

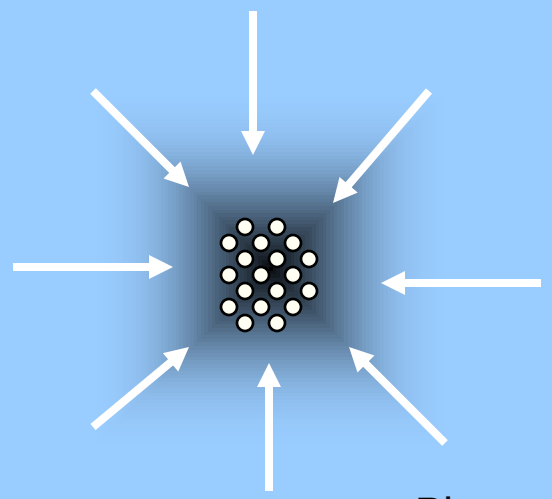
$$C_{DAW} = \frac{Z_{MC} n_{MC}}{n_i} u_{MC}$$

where

u_0 – ion drift velocity in E_0; u_{MC} – micro-cylinder drift velocity in E_0

$$Z_{MC} = 85000\text{-}170000\ e$$

2.3. Experimental investigation of boundary-free dusty plasma structures:



Uniform extended gas discharge plasma

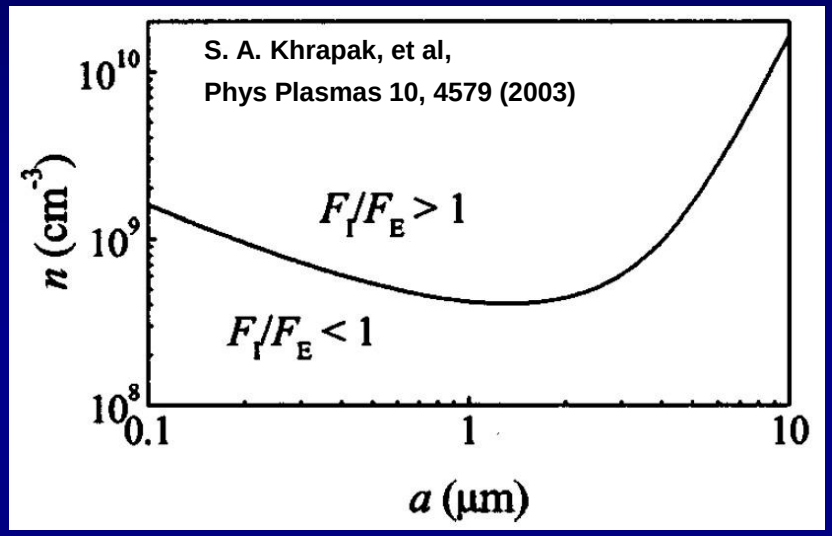
Plasma flux pressure > Electrostatic repulsion

A. D. Usachev, A.V. Zobnin, O. F. Petrov, V. E. Fortov, B. M. Annaratone, M. H. Thoma, H. Höfner, M. Kretschmer, M. Fink, and G. E. Morfill. *Formation of a Boundary-Free Dust Cluster in a Low-Pressure Gas-Discharge Plasma*. **PHYSICAL REVIEW LETTERS 102, 045001 (2009).**

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

1. Plasma recombination rate on dust particles. > Ionization rate within the dust cloud.

2.



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

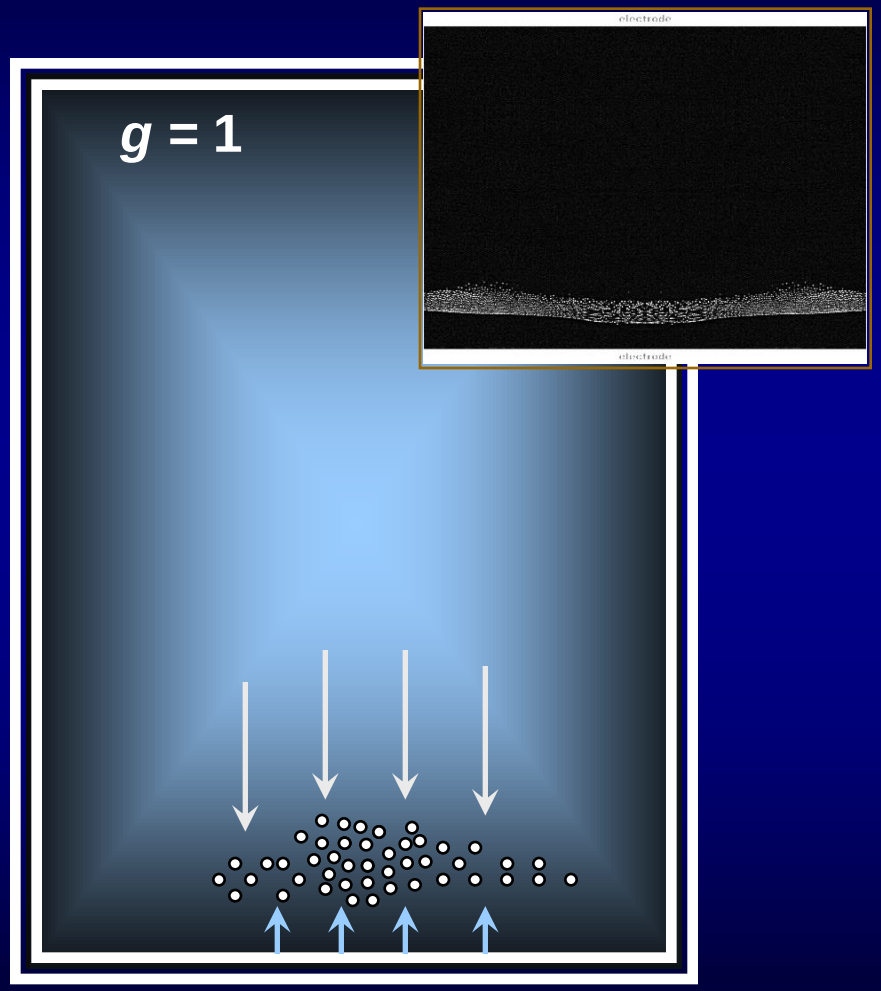
3. Condition for collective interaction

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

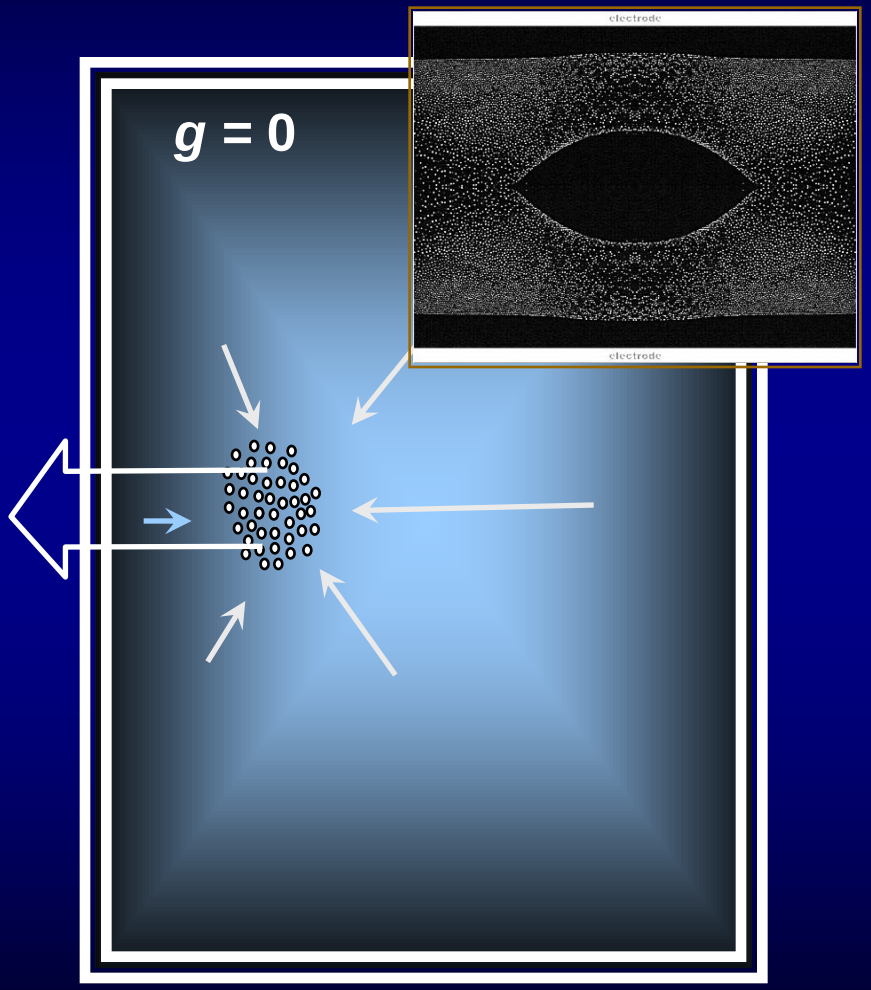
$$r_p >> 2 \text{ mcm.}$$

Real experimental conditions:

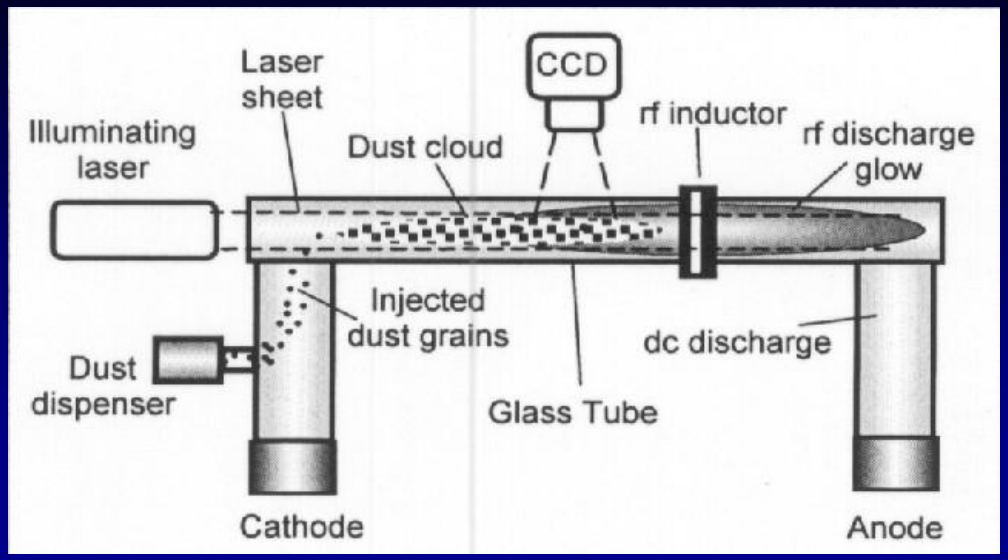
1. Under gravity boundary-free structures are not possible.



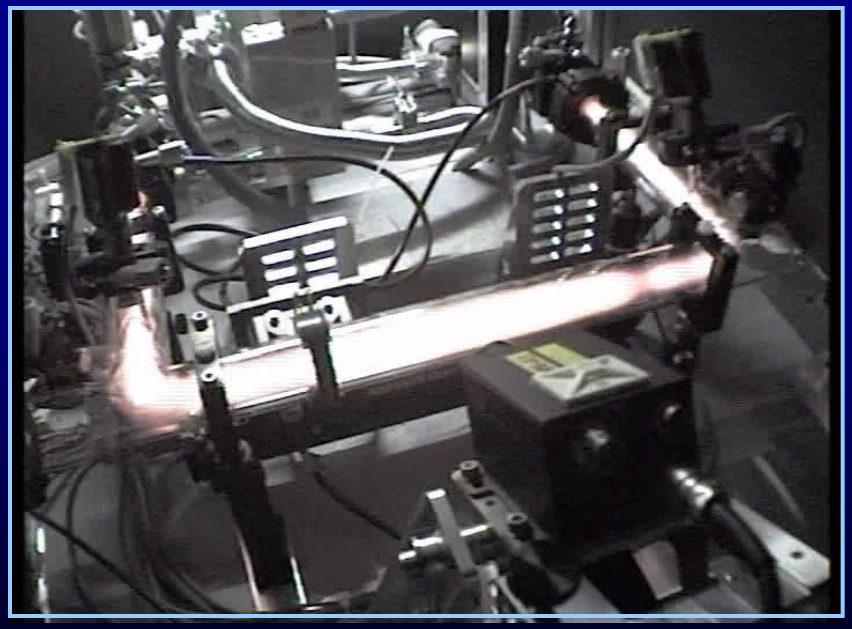
2. Dust cloud should be situated in central region of discharge chamber.



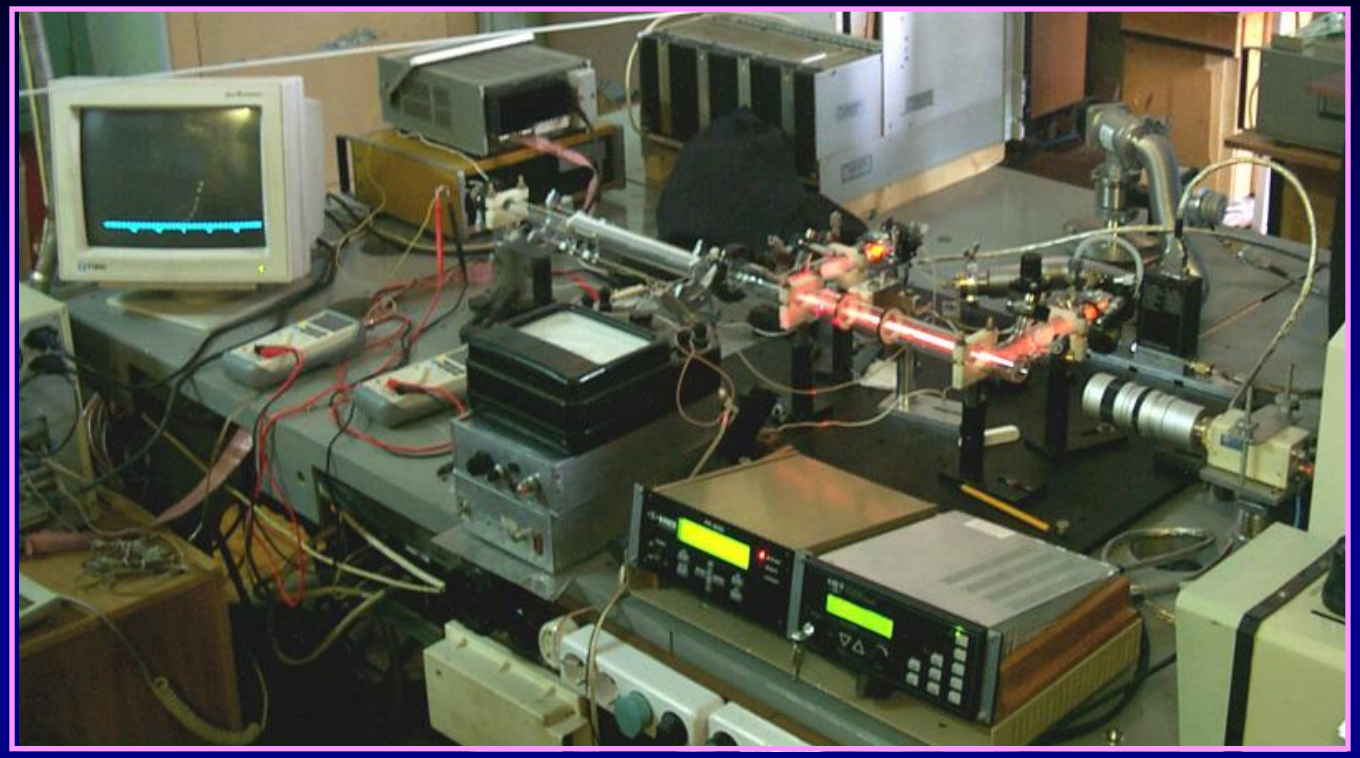
Experimental configuration of the PK-4 Setup



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



Experimental parameters:



Preliminary DC mode:	Active RF mode: (τ=180 ms)
n_i, n_e = $2\cdot10^8$ cm^{-3}	n_i, n_e = $4\cdot10^9$ cm^{-3}
T_e = 7 eV	T_e = 3.5 eV

Formation of a Boundary-Free Dust Cluster (slow down in 12 times)

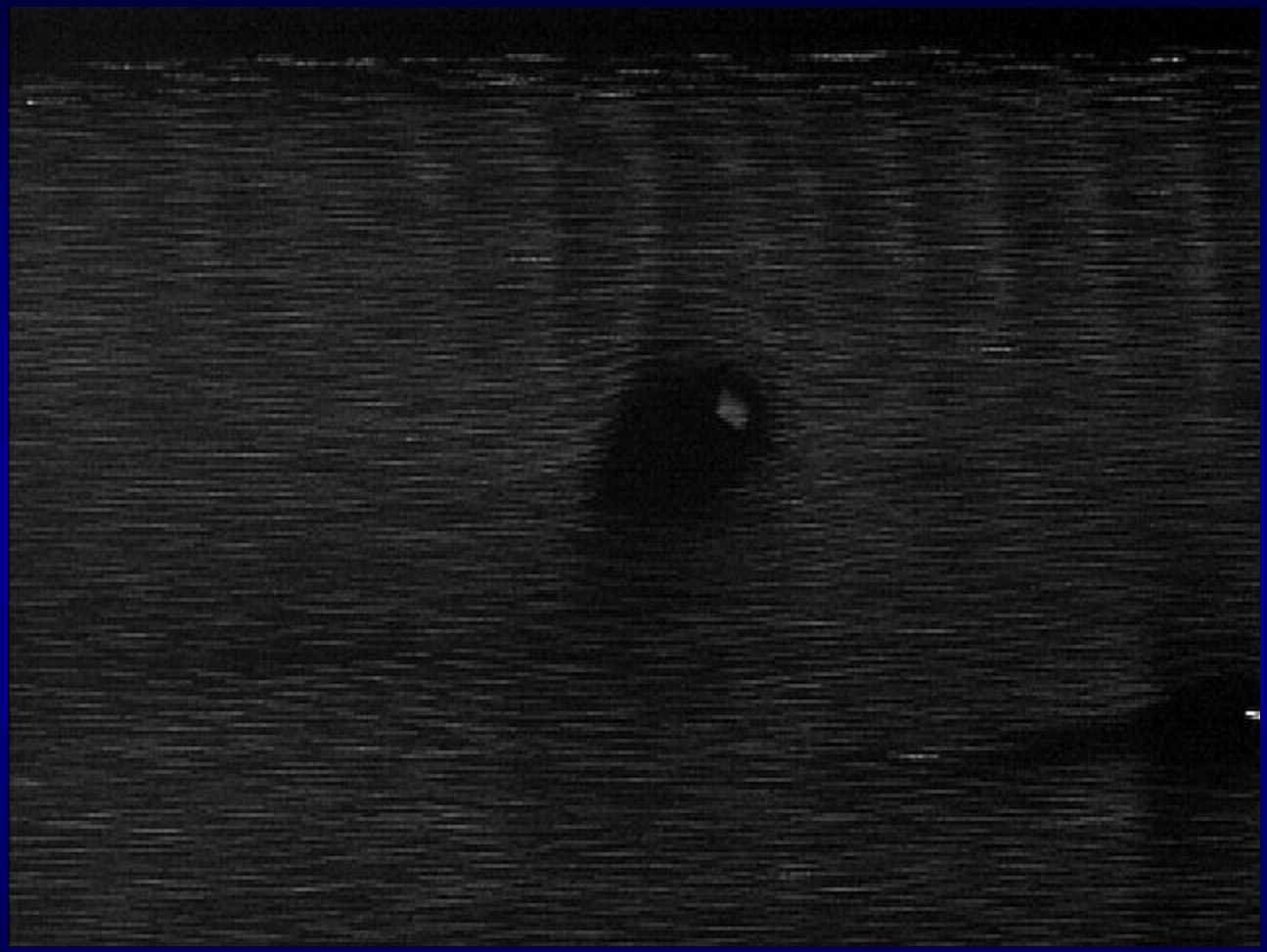


Image size: 21mm×17mm

Formation of a Boundary-Free Dust Cluster (slow down in 60 times)

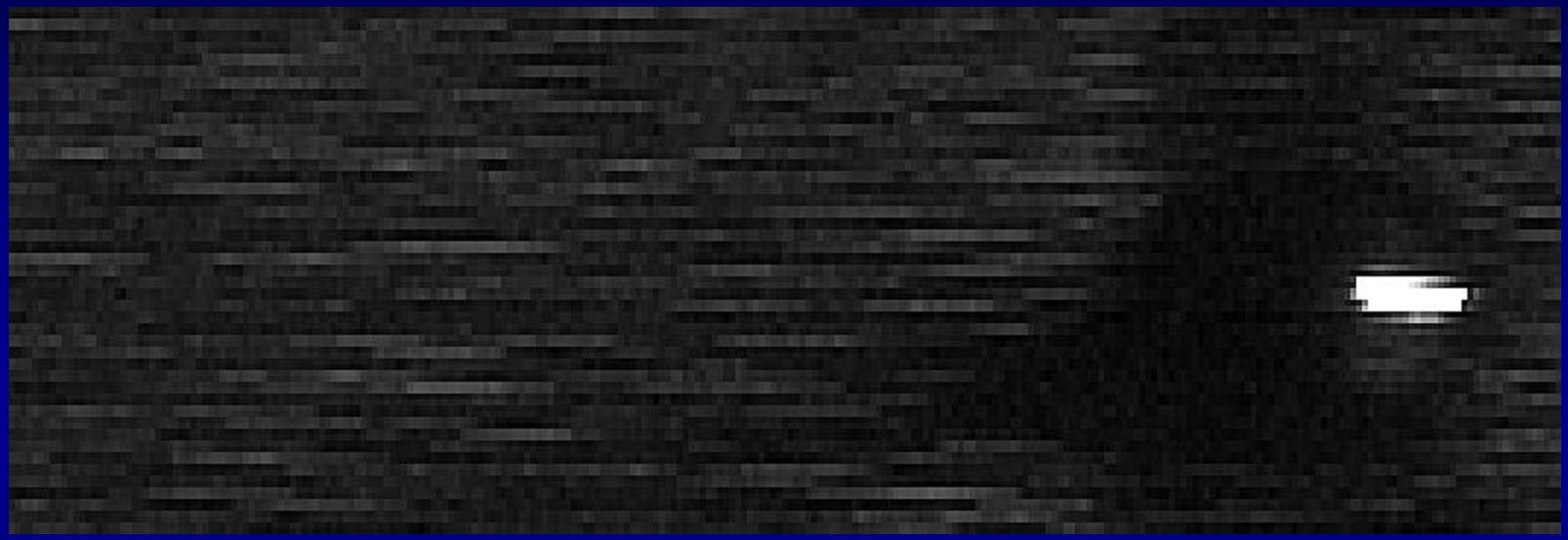
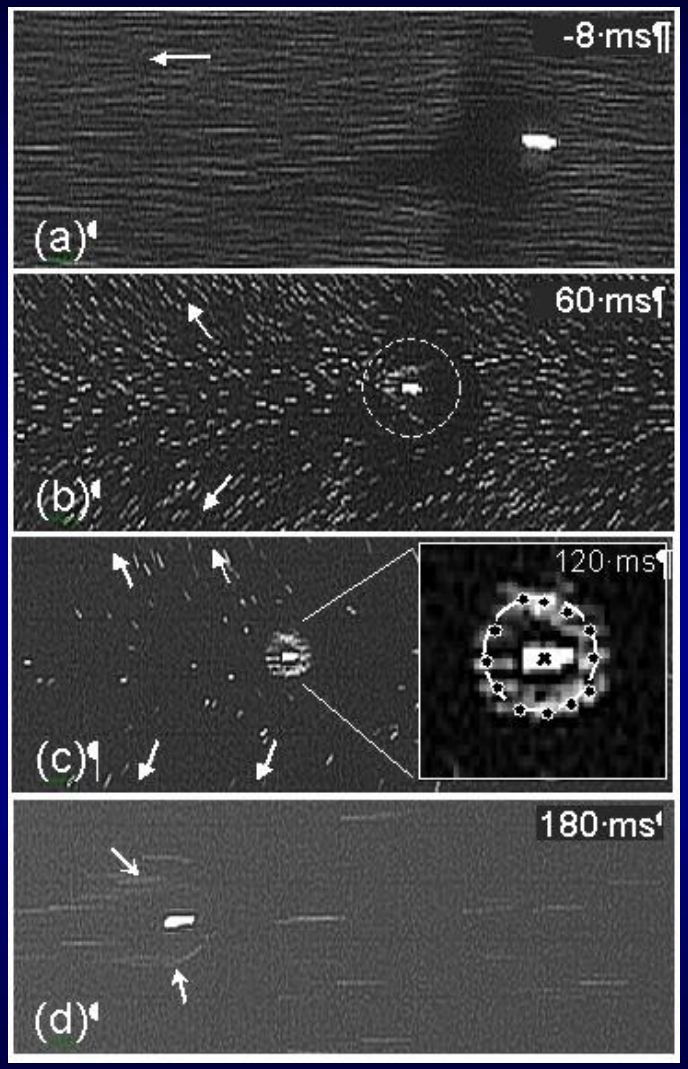
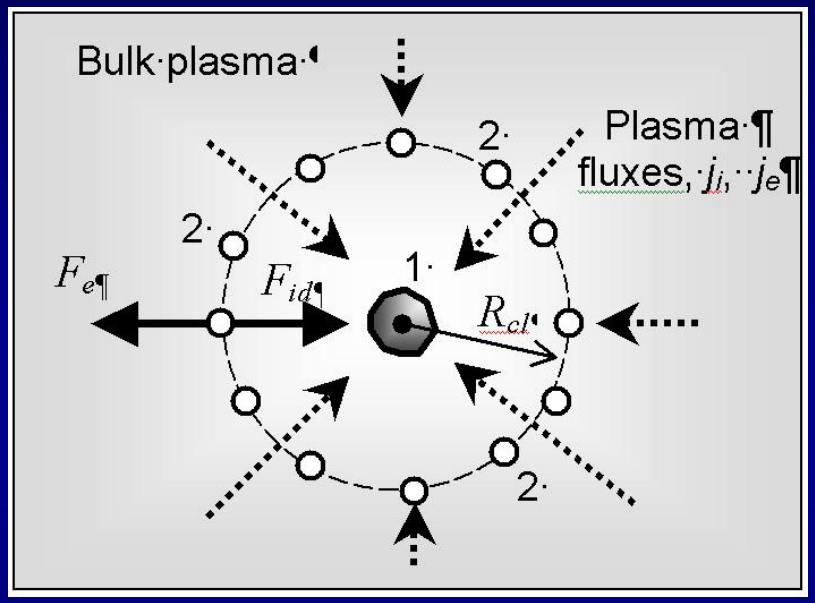


Image size: 7mm×3mm

Scheme of the Boundary-Free Dust Cluster





$\lambda_{Di} \approx 19\ \mu m$; $\lambda_{in} \approx 80\ \mu m$; $R_{cl} = 190\ \mu m$

Equilibrium condition for small particle at $r = R_{cl}$.

$$|F_i(R_{cl})| = |F_e(R_{cl})|$$

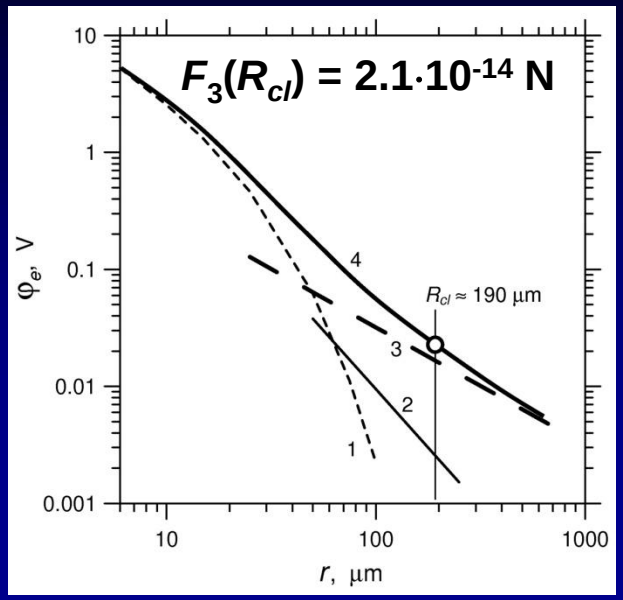
$$|F_{id}| = (2\sqrt{2}/3) m_i n_i u_i \upsilon_{T_i} r_{p2}^2 z_{p2}^2 \tau^2 \Lambda_{id}$$

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

$$z_{p2} = |Z_{p2}| e^2/4\pi\varepsilon_0 r_{p2} T_e$$

$F_{id}(R_{cl})$= 3.3·10^{-14} N

S.Khrapak, A.Ivlev, G.Morfill,
Phys. Rev. E **70**, 056405 (2004).



Electrostatic potential around the big particle calculated in different approximations :

1 – Debye-Hückel potentials with the linearized ion Debye length r_{Di} = 19 μm;

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 – φ = 3.2·10^{-6} (V·m)/r which supports ion current to the big particle in the mobility regime;

4 – self consistent numerical calculation

A.Zobnin, A.Usachev, O.Petrov, and V.Fortov
Phys. Plasmas. **15**, 043705 (2008).

Conclusion:

Microgravity conditions is quite necessary for successful dusty plasma experiments!

Acknowledgments:

German Space Agency for financial support by the grant # 50 WM 0504

European Space Agency for excellent organization of the Parabolic Flight Campaigns in Bordeaux

Russian Foundation for Basic Research for financial support by the grant # 07-02-01464-a

Special thanks to MPE engineers:

Karl Tarantik

Christian Deysenroth

Christian Rau

Sebastian Albrecht

for excellent engineering support of this work!

THANK YOU for YOUR ATTENTION!