PK-4: Complex Plasmas onboard the ISS – The Present Generation

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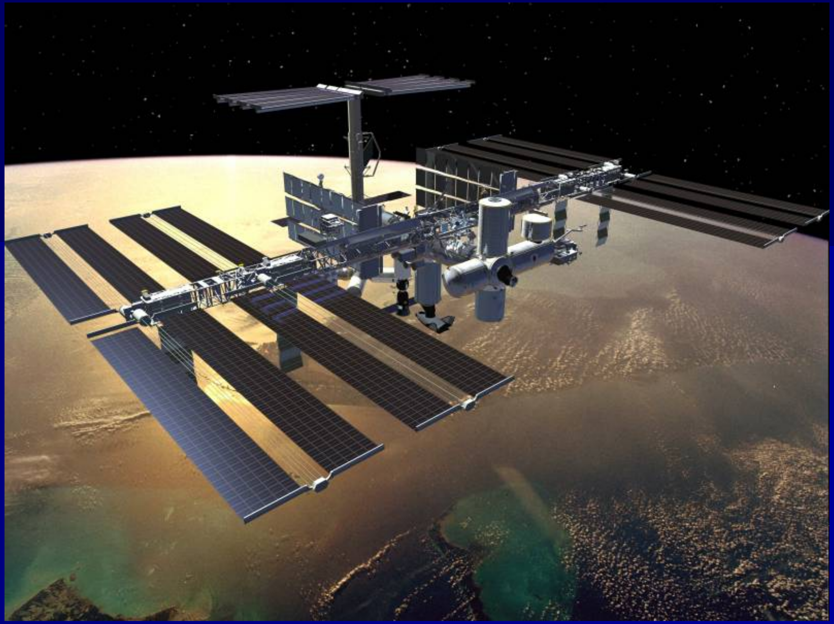
1. The PK-4 Project
2. Particle Velocities (1g vs. 0g)
3. Electrorheological Plasmas
4. Conclusions and Outlook

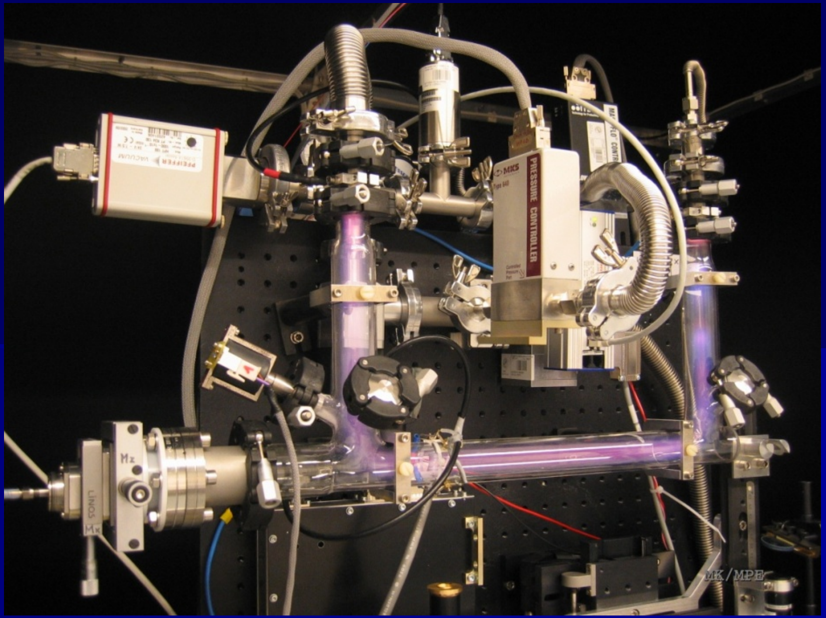
1. The PK-4 Project

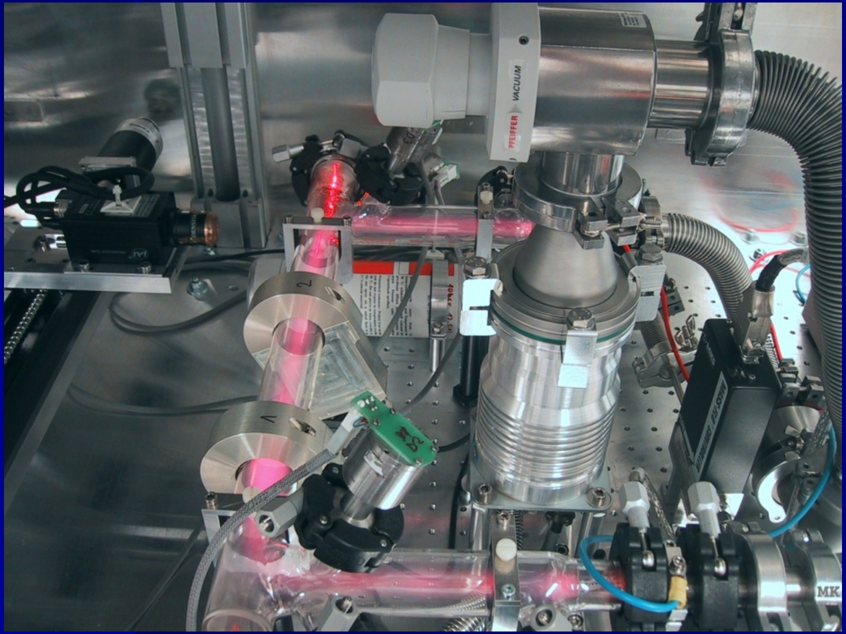
- Aim: Investigation of complex DC plasmas under microgravity on ISS
- Successor of PKE-Nefedov and PK-3 Plus
- Accomodation: EPM Rack in Columbus Module (ESA project)
- Launch from Baikonur with Progress in October 2014
- Commissioning Experiments June 2015



Construction of a laboratory and a parabolic flight unit started in 2002 (supported by DLR)

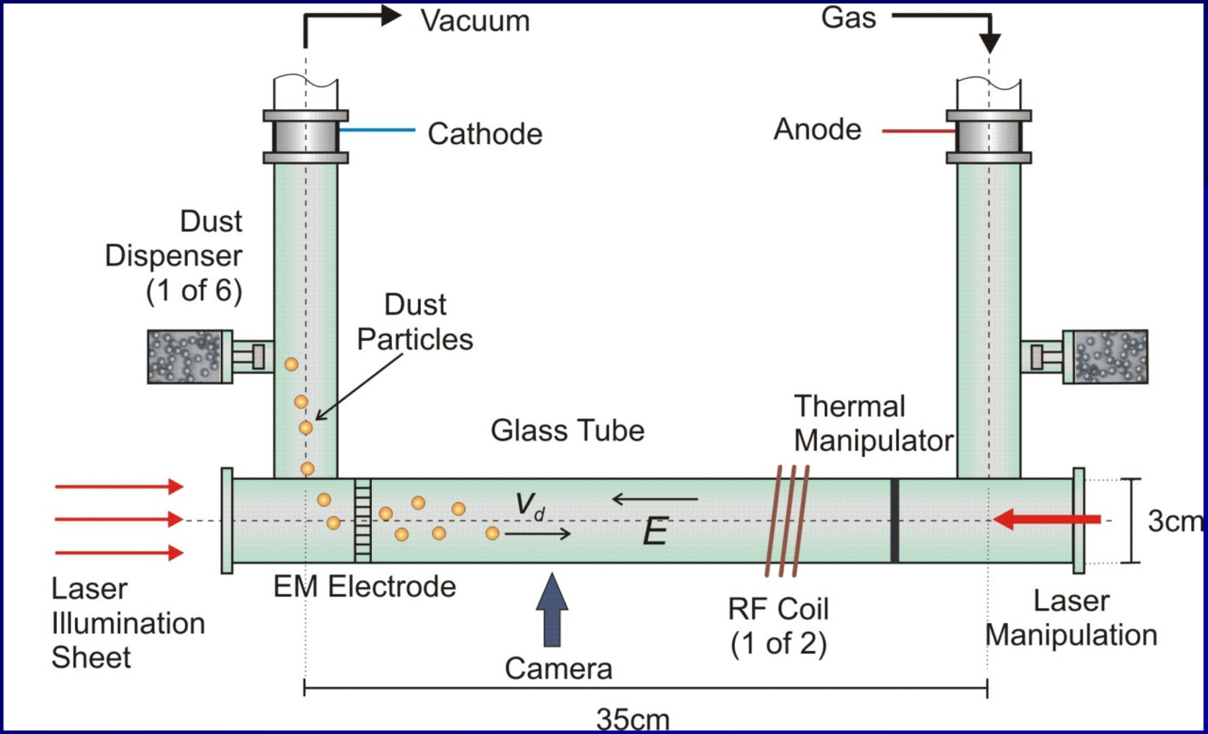
→experiments and apparatus development and tests including 9 ESA and DLR Parabolic Flight Campaigns





Description and technical data (ISS flight model)

Experiment unit:



- DC plasma chamber (glass tube, 45 cm long, 3 cm diameter) with cylindrical electrodes

- HV generator
  V = 0 - 3 kV

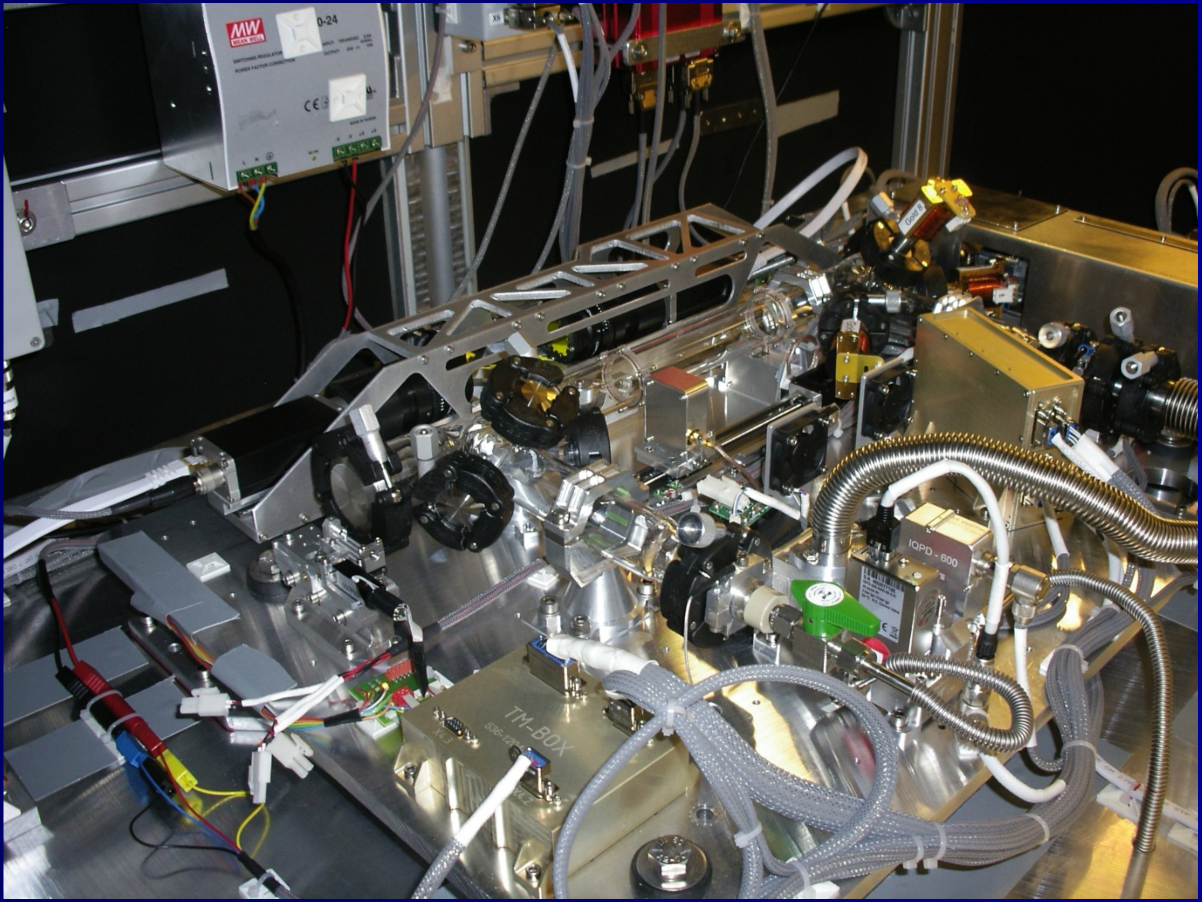
- Gas/vacuum system, turbo molecular pump
  Minimum pressure $<10^{-3}$ Pa, operation pressure: 5 - 250 Pa, gas flow: 0 -10 sccm (Neon, Argon)

- 6 dispensers (3 gas jet dispensers, 3 shaker dispensers)

- Illumination laser (sheet)

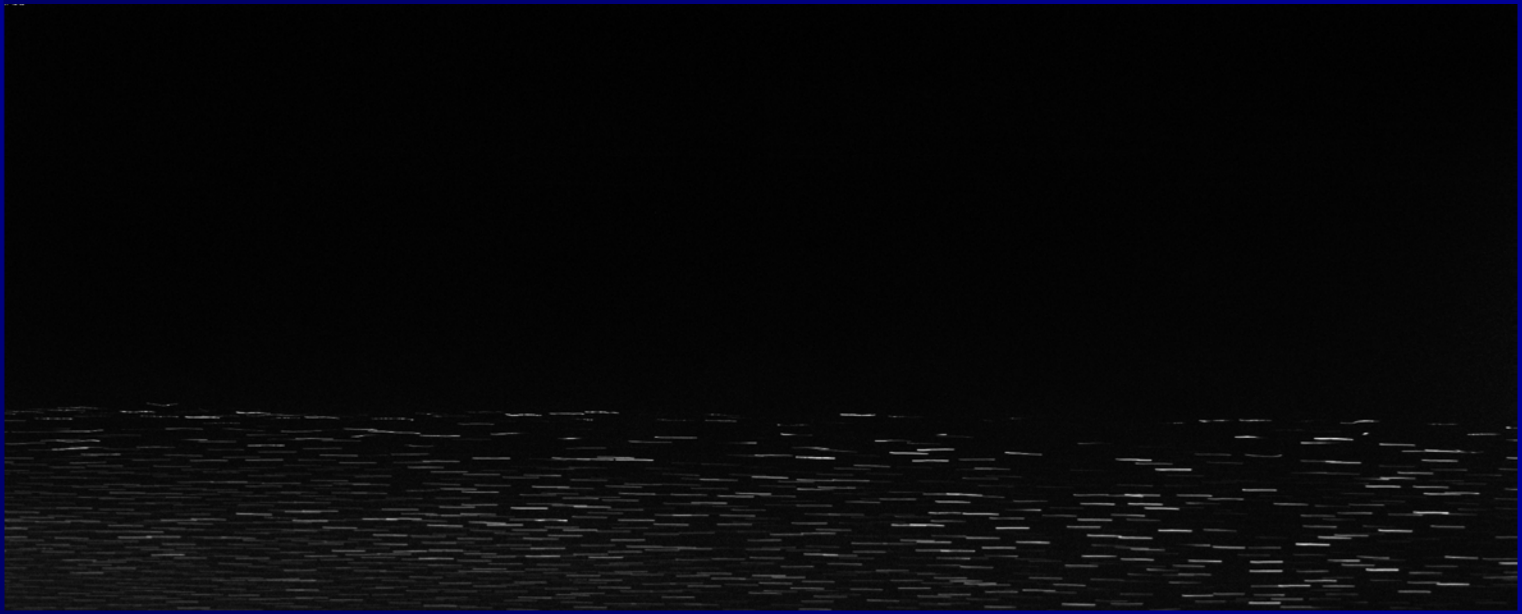
- 2 CCD cameras for particle observation (2 MPixel, 0- 200 Hz, movable), 1 overview camera (plasma glow), spectrometer

- Particle manipulation:
  2 RF coils (RF generator 0-5 W), laser (diode, infrared, 0-25 W), heating wire for thermal manipulation, DC electrode inside of chamber, DC modulation (0-200 Hz), polarity switching of DC (0.1 - 5 kHz)



Experiments with PK-4

- Glass tube in particular useful for investigation of liquid phase of complex plasmas, e.g. transition from laminar to turbulent flow on microscopic level
- All experiments influenced by gravity or impossible
- Basic measurements: positions and velocities of the microparticles (1 - 10 cm/s), particle correlations



Published investigations with PK-4:

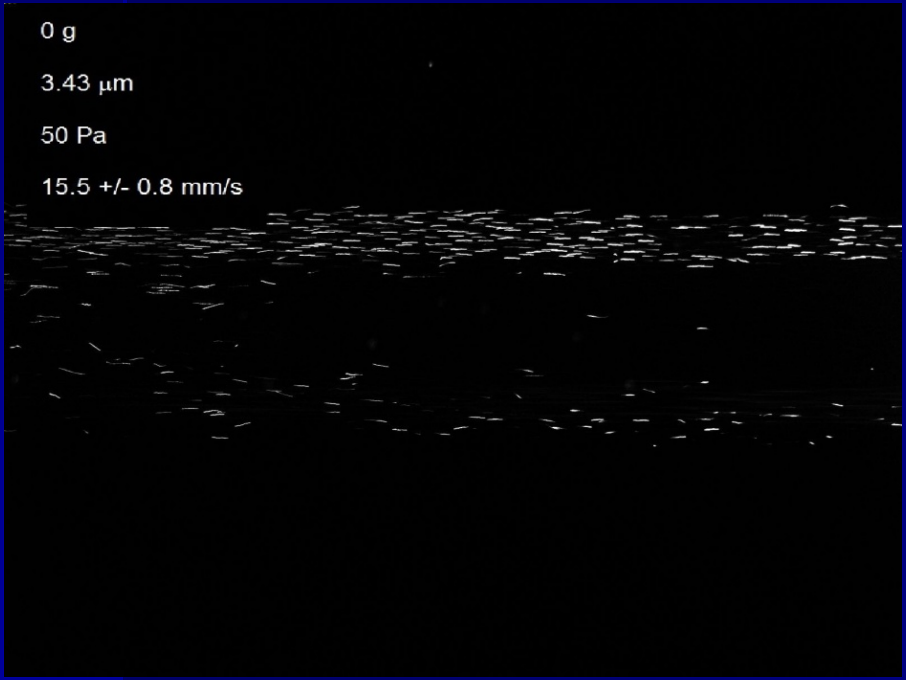
1. Determination of Particle Charge
   S. Ratynskaia et al., PRL 93 (2004) 085001, S. Khrapak et al., PRE 72 (2005) 016406, S. Khrapak, Phys. Rev. E 87 (2013) 063109
2. Measurement of Ion Drag Force
   V. Yaroshenko et al., Phys. Plasmas 12 (2005) 093503
3. Shear Flow and Non-Newtonian Viscosity
   A. Ivlev et al., PRL 98 (2007) 145003
4. Ordered 3D structures
   S. Mitic et al., PRL 101 (2008) 125002, S. Mitic et al., Phys. Plasmas 20 (2013) 043701
5. Double layer formation
   V. Yaroshenko et al., Phys. Plasmas 15 (2008) 082104
6. Dust convection and thermal creep
   S. Mitic et al., PRL 101 (2008) 235001
7. Boundary free cluster
   A. Usachev et al., PRL 102 (2009) 045001
8. Dissipative Dark Solitons
   S. Zhdanov et al., Eur. Phys. Lett. 89 (2010) 25001, R. Heidemann et al., IEEE Trans. Plasma Sci. 39 (2011) 2720
9. Electrorheological Plasma
   A. Ivlev et al., PRL 106 (2011) 155001
10. Spectrocopy of complex plasmas
    S. Mitic et al., Optics Letters 36 (2011) 3699, S. Mitic et al., J. Phys. D: Appl. Phys. 45 (2012) 335203
11. Particle Formation and Transport
    L. Wörner et al., New J. Phys. 14 (2012) 023024
12. Grain Charging in Intermediately Collisional Plasma
    S. Khrapak et al., EPL 97 (2012) 35001
13. Pearl-necklace-like Structures of Microparticle Strings
    M.A. Fink et al., Phys. Rev. E 86 (2012) 065401(R)
14. Particle Flows in Laboratory and Microgravity Conditions
    S. A. Khrapak et al., Phys. Rev. E 87 (2013) 063109
15. Autowaves Confined behind a Laval nozzle
    M. Fink et al., EPL 102 (2013) 45001
16. Externally Excited Planar Dust Acoustic Shock Waves
    A. Usachev et al., New J. Phys. 16 (2014) 053028

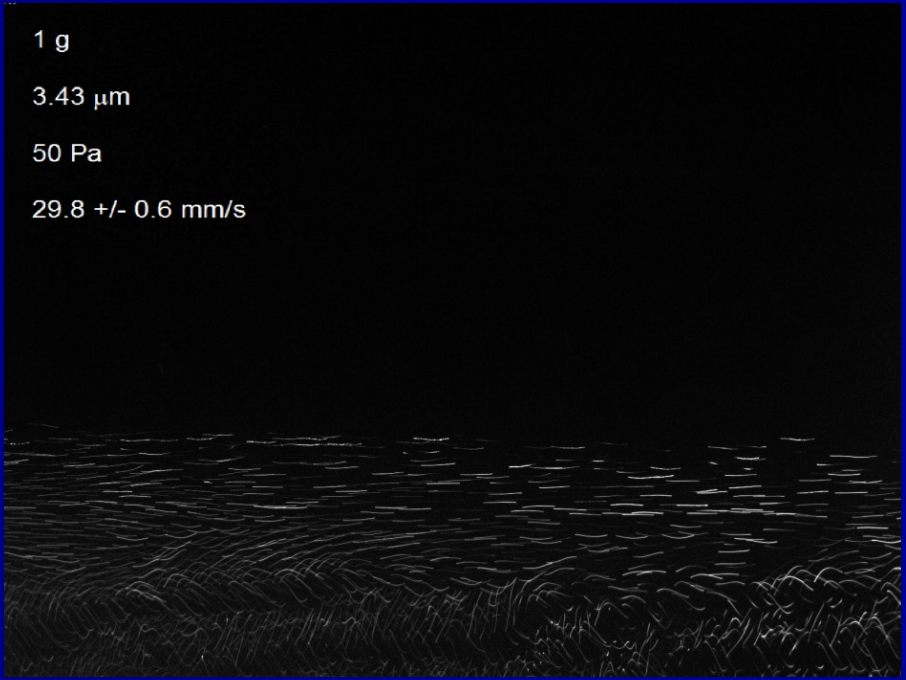
2. Particle Velocities (1g vs. 0g)

Observation: Microparticles in microgravity slower than on ground

16 parabolas in 57th ESA Parabolic Flight Campaign (October 2012)

Neon
Particle diameter: 2.55, 3.43, and 6.86 µm
Pressure: 30, 50, 70, and 90 Pa
DC current: 1 mA





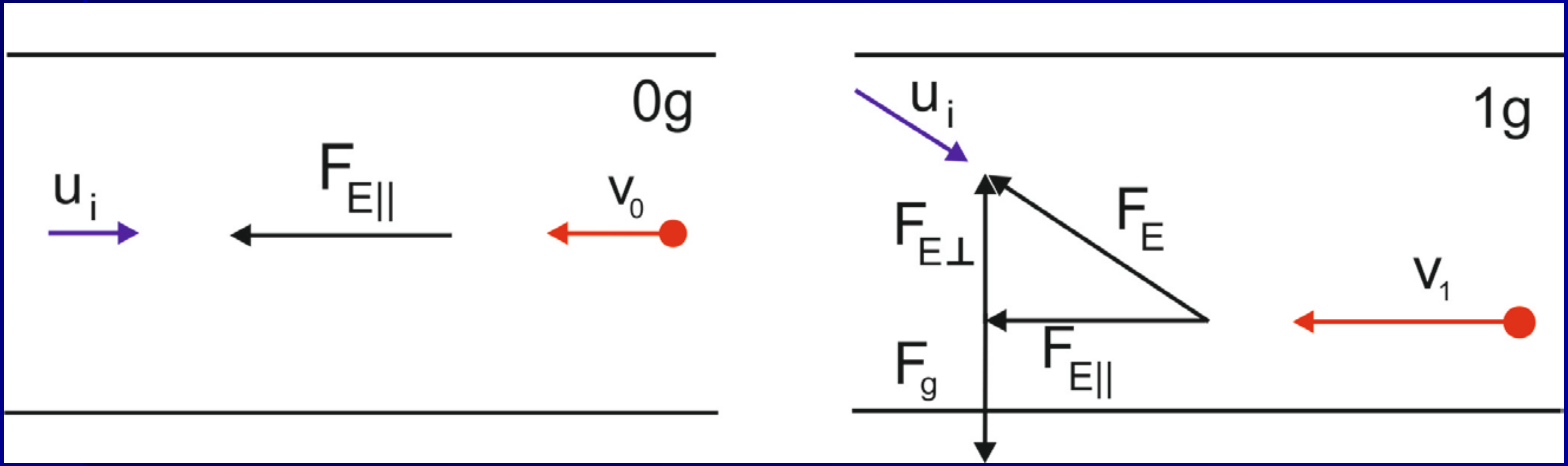
Reason: microparticles are located closer to bottom of tube (horizontal position) in 1g

→ electric field increases due to vertical component compensating gravity

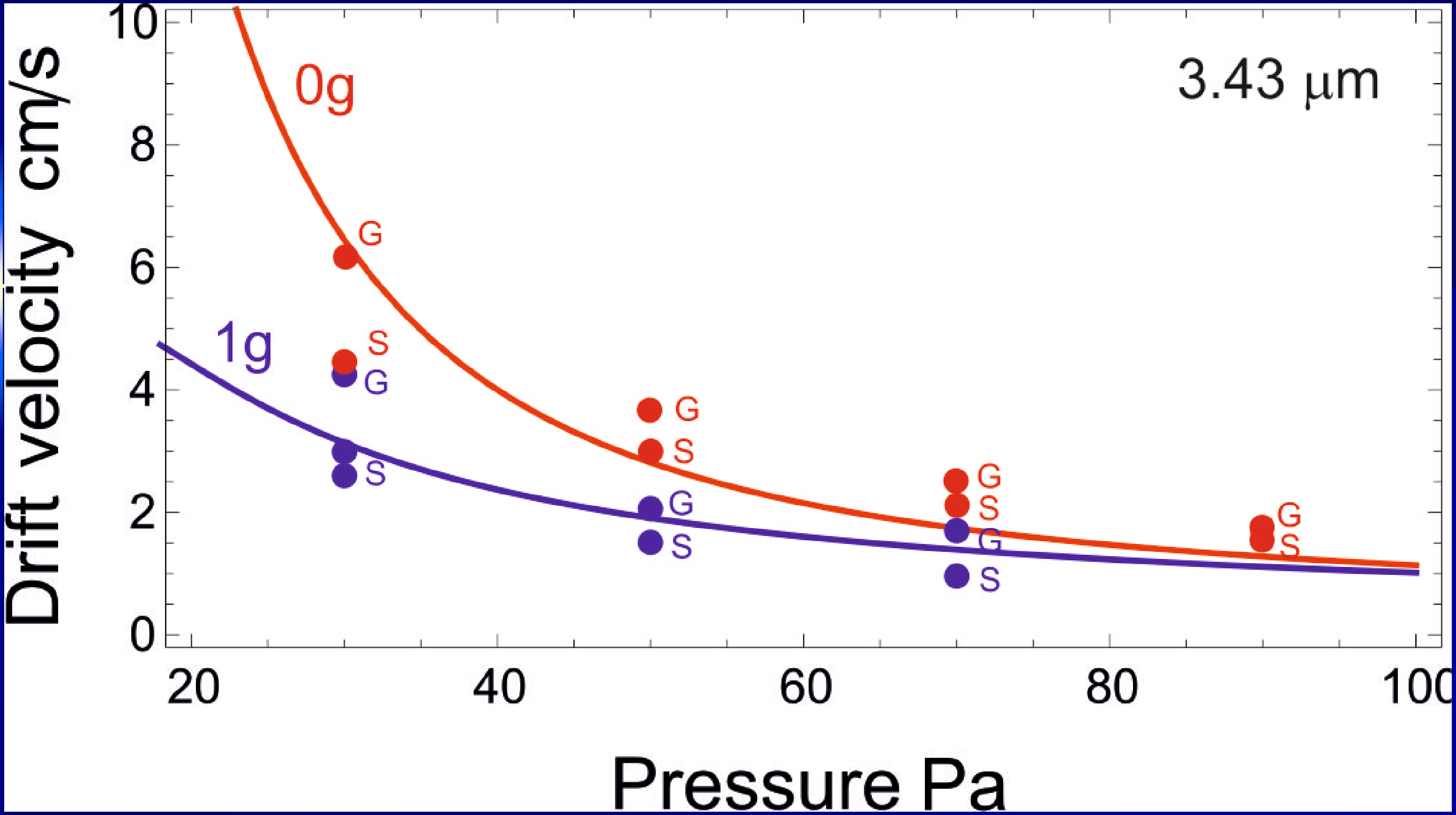
→ ion drift velocity increases

→ increase of negative particle charge

→ increase of particle velocity



S. A. Khrapak et al., Phys. Rev. E 87 (2013) 063109



Dots: data (G: gas jet dispenser, S: shaker dispenser)
Solid curves: theoretical prediction

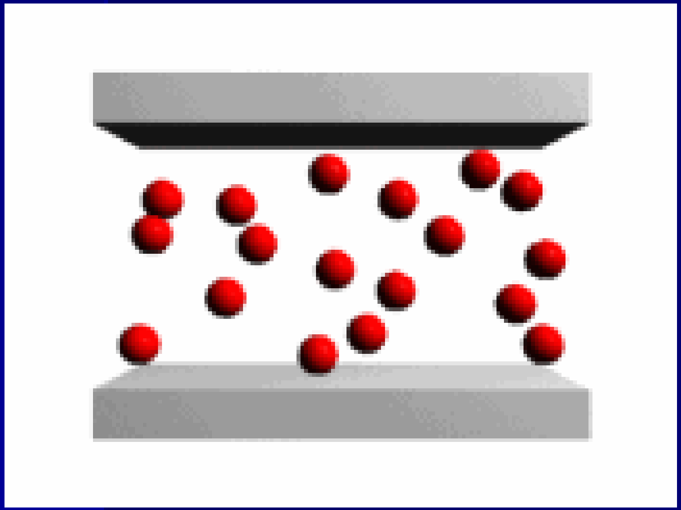
Particles injected from gas jet dispsensers are faster than from shaker dispensers due to gas flow induced by gas jet dispensers

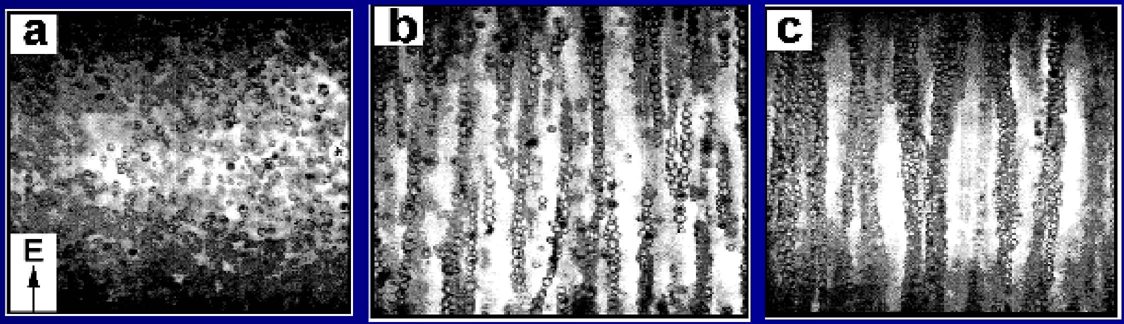
3. Electrorheological Plasma

Electrorheological fluids: suspensions of nano- or microparticles in a non-conducting fluid

External electric (or magnetic) field → drastic change of properties,
e.g. strong increase of viscosity → technological applications, e.g. shock absorber, brakes, …

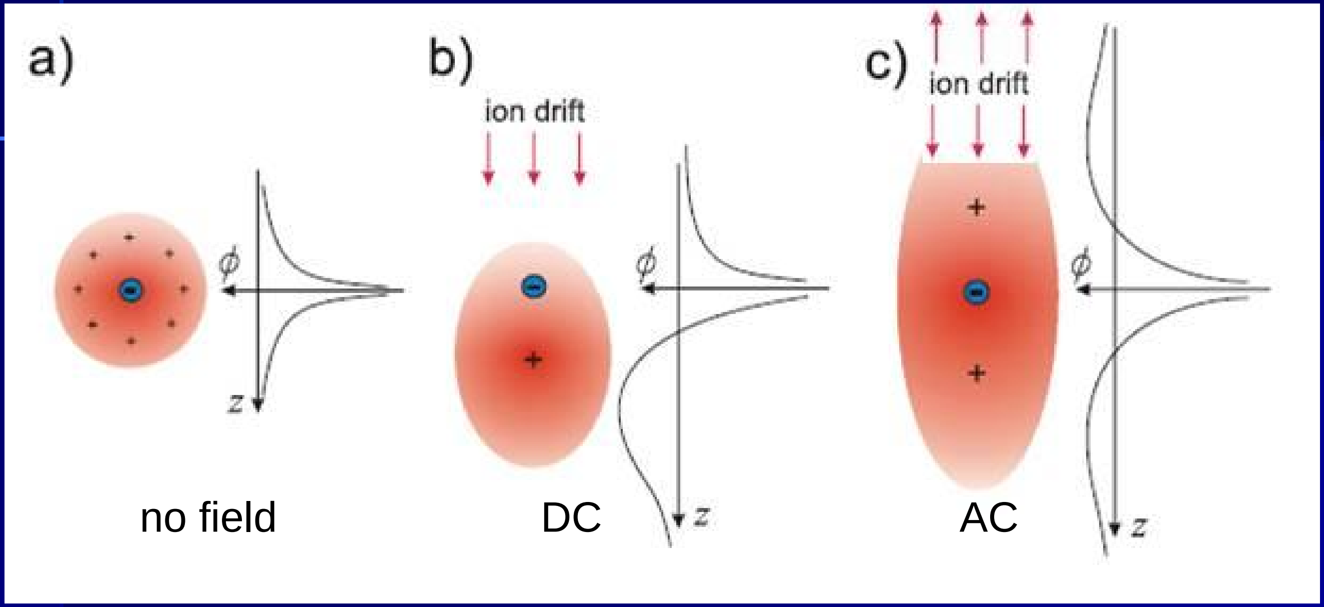
Reason: modification of interaction between microparticles due to external field
→ anisotropic string formation





P. Sheng et al. (2007)

Complex plasma with external electric AC field
→ attractive dipole-dipole interaction
→ formation of strings of microparticles



no field

DC

AC

Interaction potential between microparticles

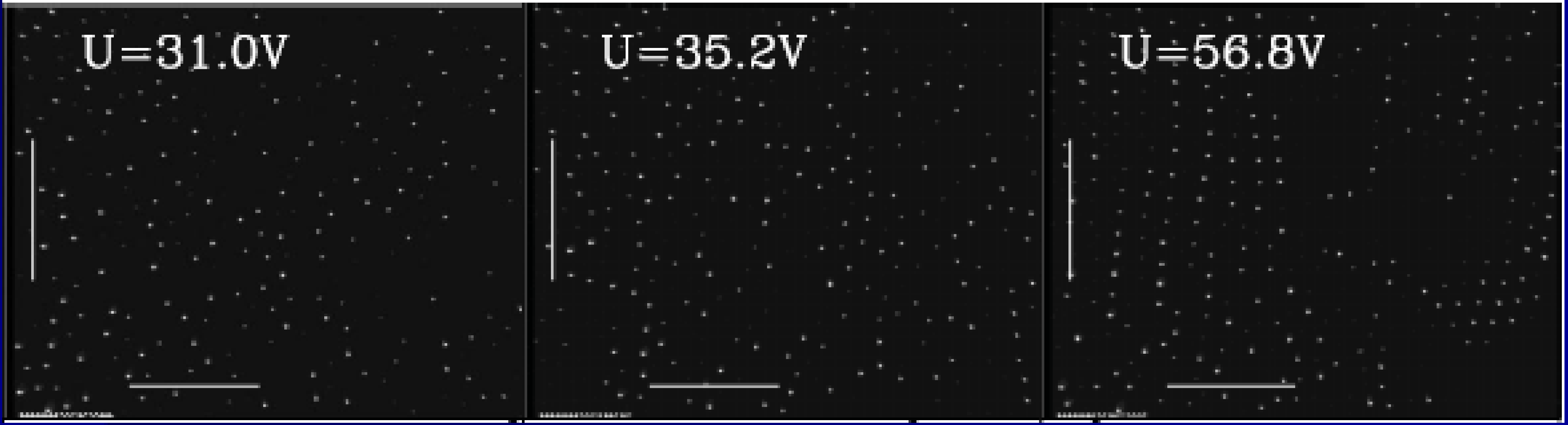
$$W(r,\theta) \simeq Q^2\left[\frac{e^{-r/\lambda}}{r} - 0.43\,\frac{M_T^2\lambda^2}{r^3}\left(3\cos^2\theta - 1\right)\right],$$

Mach number: M_T = ion drift velocity / thermal ion velocity
Debye screening length: λ

First observation of electrorheological plasmas with PK-3 Plus on ISS

Phase transition from isotropic to stringfluid with increasing electric field

A.V. Ivlev et al., PRL 100 (2008) 095003



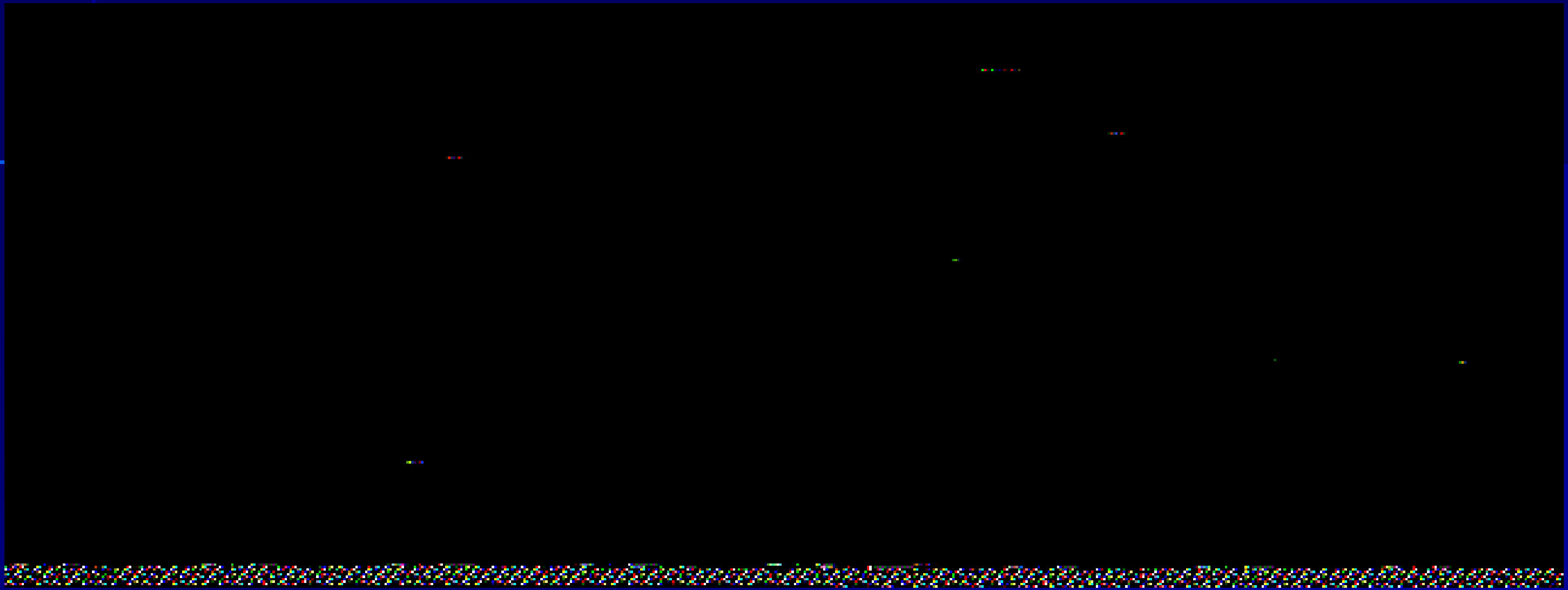
Electrorheological Experiments with PK-4

Polarity switching of DC with frequency (e.g. 1 kHz) much higher than dust plasma frequency but much lower than ion plasma frequency
→ stable microparticle clouds, streaming ions changing direction
→ attractive dipole-dipole interaction between microparticles
→ electrorheological plasma

Parabolic flight experiments (30 parabolas) in November 2008 (49th ESA Parabolic Flight Campaign) and February 2009 (13th DLR Parabolic Flight Campaign)
→ particles in tube center (bulk plasma)

Gas: Neon
DC current: 1 and 3 mA → longitudinal electric field 2 V/cm
Particle diameter: 3.43 and 6.86 μm
Pressure: 15 – 100 Pa
Mach number: $M_T = 22/p[\mathrm{Pa}] = 0.2 – 1.5$

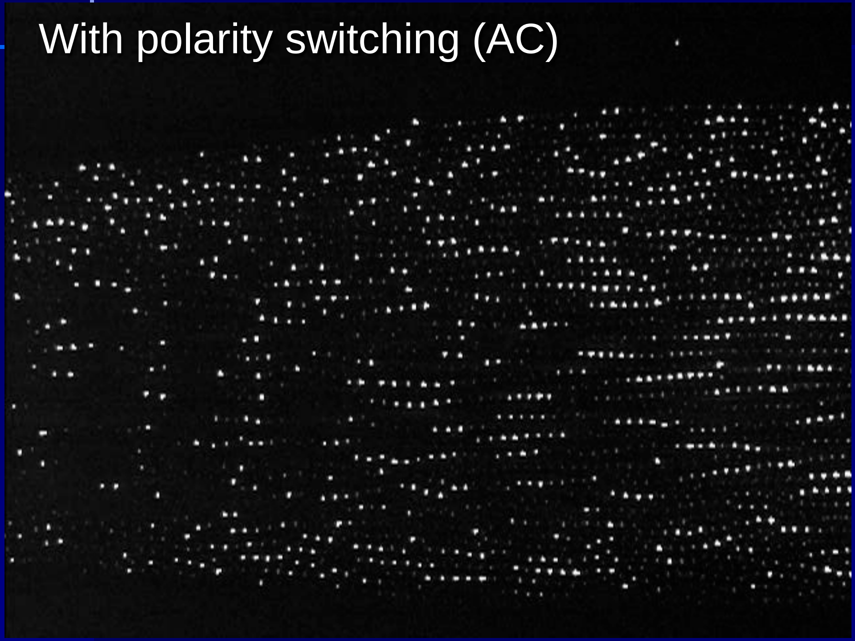
I = 1 mA, d = 6.86 μm, p = 60 Pa, $M_T \sim 0.4$

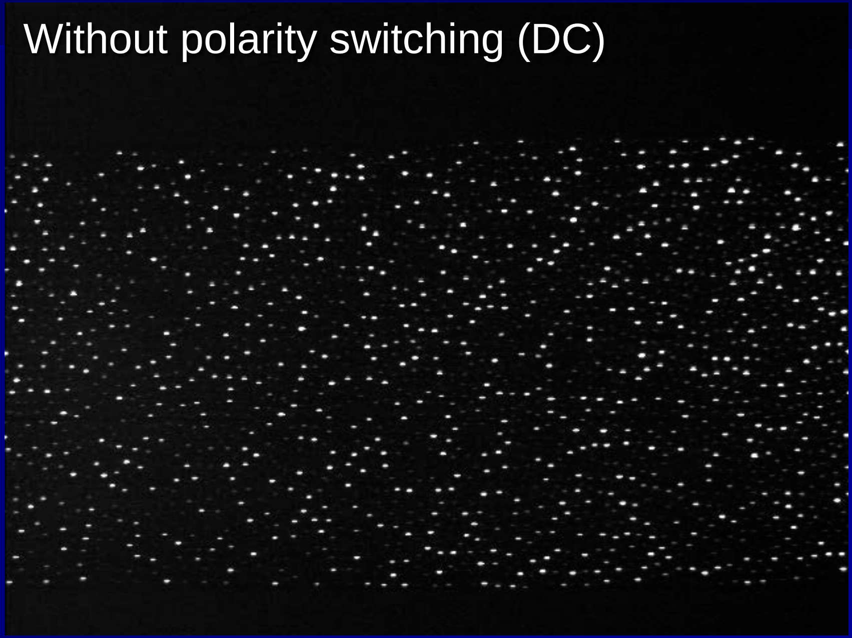


String formation decreases with increasing pressure p since Mach number proportional to 1/p (dipole-dipole interaction $W \sim M_T^2 \sim 1/p^2$)

String formation decreases with increasing current leading to increasing ion density n_i and decreasing Debye screening length ($W \sim \lambda^2 \sim 1/n_i$)

No string formation observed in pure DC case for same parameters (pressure, current, particle size) as in AC (polarity switching)

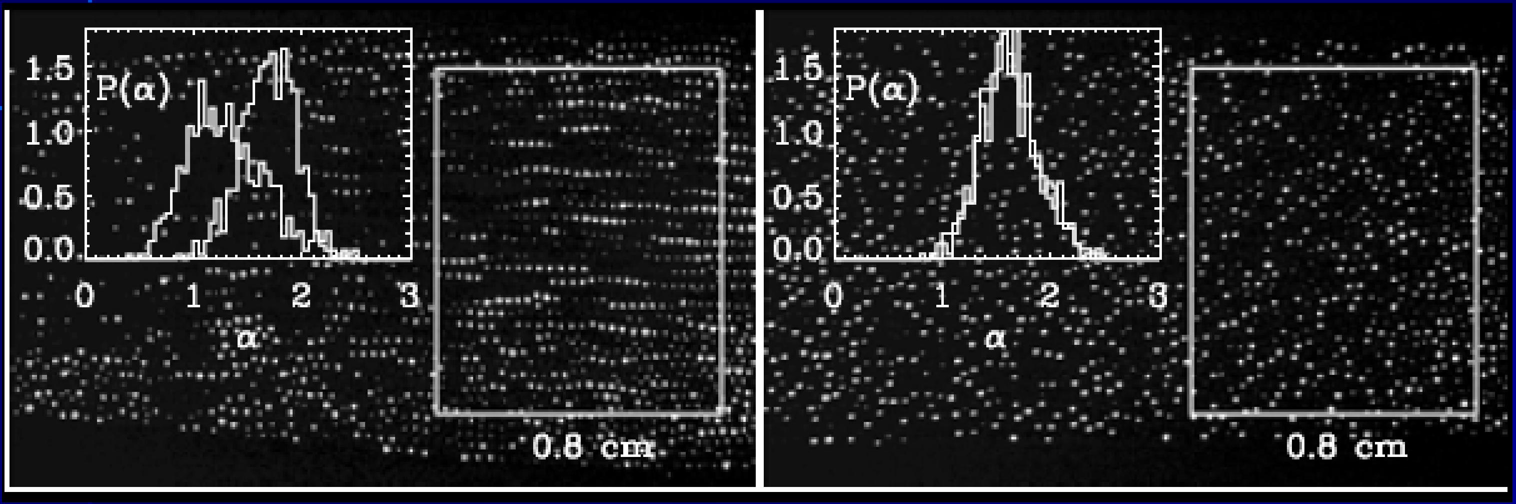

With polarity switching (AC)


Without polarity switching (DC)

p = 60 Pa ($M_T \sim 0.4$)

Scaling index analysis (C. Räth)

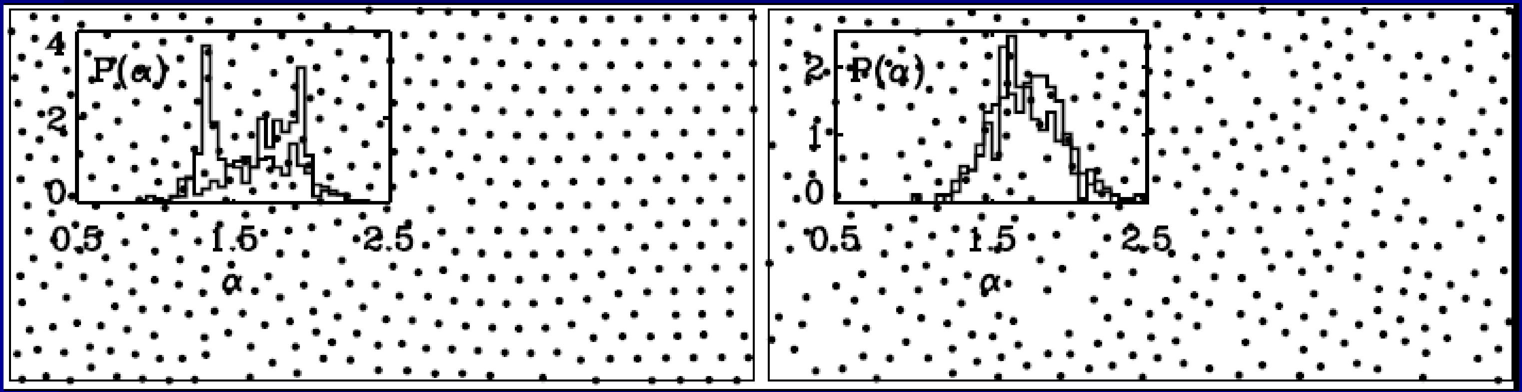
AC DC



MD simulation (G. Joyce)

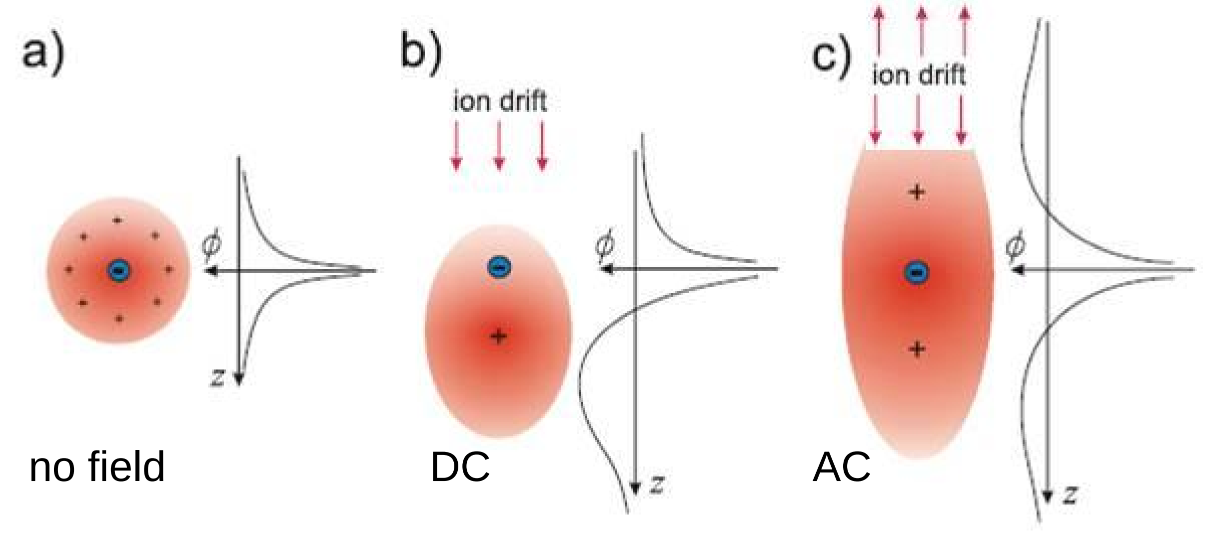
p = 60 Pa (M_T ~ 0.4)

AC DC



Why is string formation absent in the DC case?

Wake potential in DC stronger attractive than dipole-dipole interaction in AC
→ string formation should be stronger in DC than AC



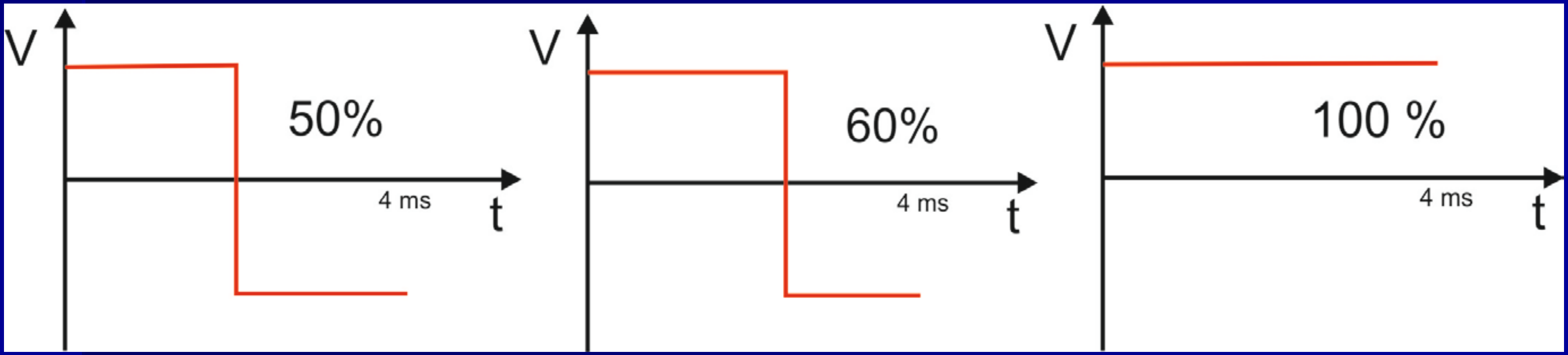
However, wake potential in DC case is non-reciprocal
→ non-Hamiltonian system
→ open system (energy gain from outside)
→ convective instability preventing string formation,
confirmed by experiments and MD simulations

A. Ivlev et al., PRL 106 (2011) 155001

Phase transition from string fluid to isotropic system

20 parabolas in 57th ESA Parabolic Flight Campaign (October 2012)
Particle diameter: 6.86 μm
Pressure: 40 Pa and 60 Pa
DC current: 1 mA and 0.6 mA
Polarity switching frequency: 250 Hz
Duty cycle: 50%, 55%, 60%, 70%, 100%

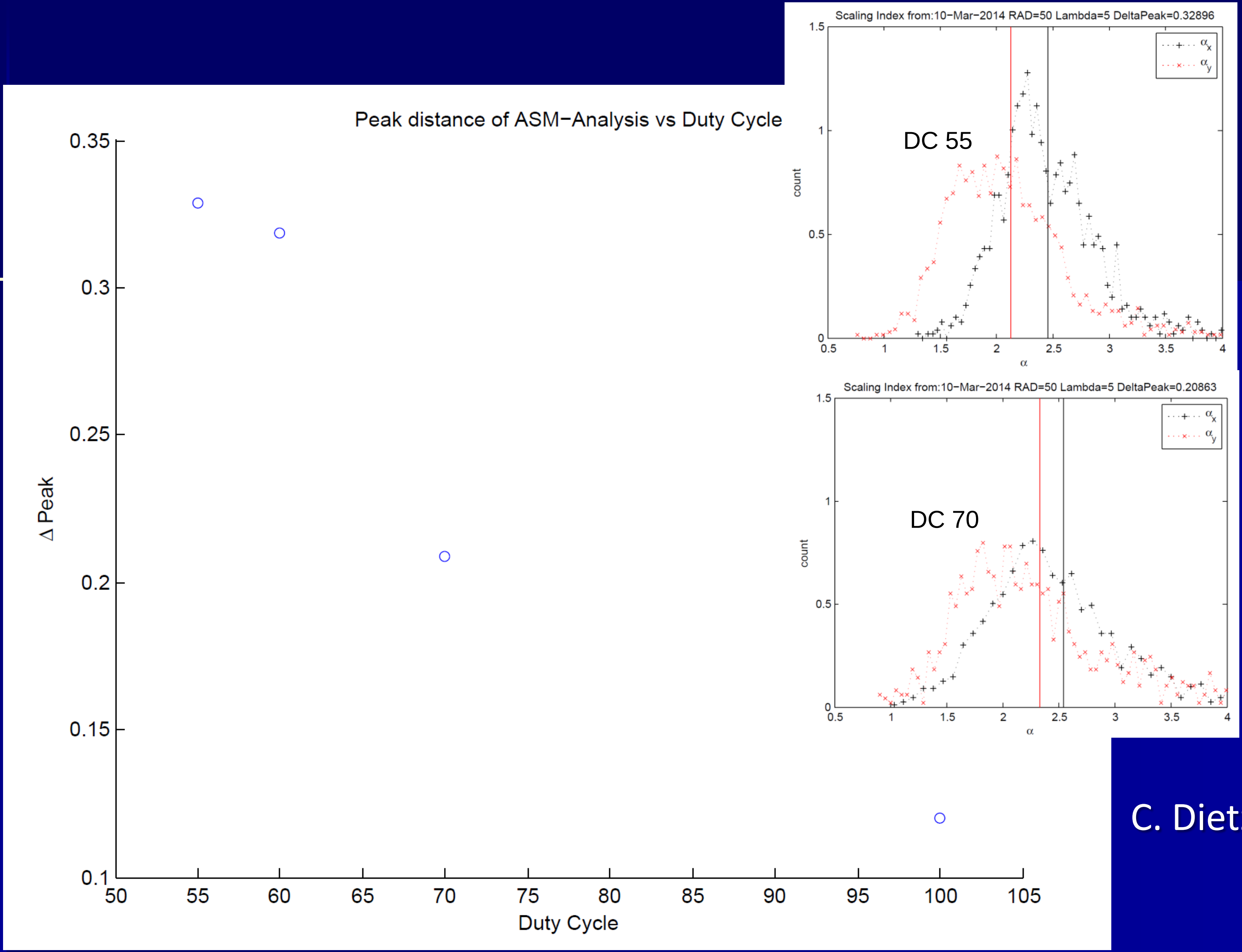
Change duty cycle of polarity switching from 50% (symmetric potential in AC, stable system) to100% (wake potential in pure DC, particle flow)



Phase transition at about 70% duty cycle

Duty Cycle 55%, 60 Pa, 1 mA

Duty Cycle 70 %, 60 Pa, 1 mA



C. Dietz

More microgravity experiments needed

Conclusions

1. PK-4: investigation of complex plasmas in a dc discharge in the laboratory and under microgravity (parabolic flights, ISS)

2. Various manipulation (gas flow, dc modulation, rf coils, laser, heating coil) and diagnostic (discharge housekeeping data, plasmas glow, spectrometer) devices → universal experiment facility

3. Particularily (but not exclusively) suited for flow phenomena

4. Already interesting investigations in the laboratory and parabolic flight experiments, e.g. phase transitions in electrorheological and non-Hamiltonian systems, different particle velocities in 0g and 1g experiments

Outlook

- Operation onboard ISS starting in 2015, operation center CADMOS (Toulouse)
- June 2015: Commissioning experiments → complete functionality tests
- 4 experiment missions (1 week) per year planned at least until 2019
- Pool of possible experiments proposed by Facility Science Team:

Particle charge
Ion drag
Waves
Trap technique tests
Structural properties
Electrorheological experiments
Diffusion
Structural properties
Phase transitions
Test of trapping by RF coil
Structural properties
Dust waves & Plasma Instability
Thermodynamics “steady state”
Shocks & Mach cones
Rarefaction waves
Laval nozzle
Micro-fluidic nozzle

Shear flow
Viscosity
Lane formation
Transition from laminar to turbulent flow
Critical Point
Crystallisation
Crystallisation under compression
Induced Dust Acoustic Waves (DAWs) in elongated dust clouds
Spontaneous DAWs
Boundary-free dust clusters & clouds
Heat transfer
Structural properties
Phase transitions
Phase transitions under external influence
Complex plasma relaxation
Externally excited transverse waves in steady state solids

More experiment proposals welcome!

Thank you very much for your attention!