From the NanoWorld
to StarDust

NW2SD

International Conference

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Palais du Pharo

Complex/Dusty Plasma Physics – from Laboratory to Space

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Outlook

Introduction Plasma and Dusty Plasma

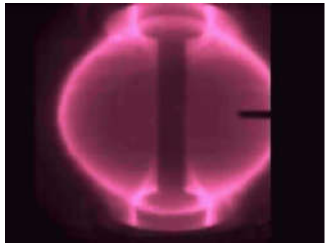
History of Dusty Plasma Research

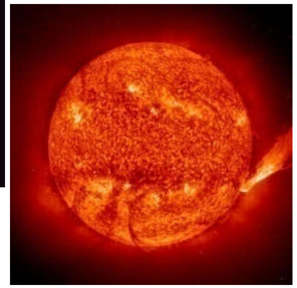
Experiments in the Laboratory

Experiments in Space

Conclusion and Outlook

What is a Plasma?





gas → ionisation → plasma

plasma → recombination → gas

gas ↔ liquid: evaporation / condensation

Plasma:

- fourth state of matter
- most disordered state of matter
- 99% of the visible Universe is Plasma

solid → melting → liquid

liquid → crystallisation → solid

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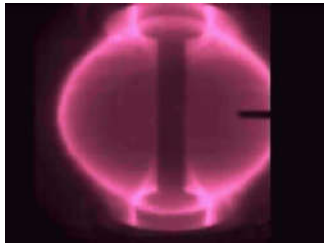
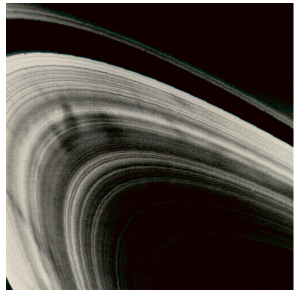
What is a Dusty Plasma?





gas ⟷ (partly) ionised ⟷ plasma

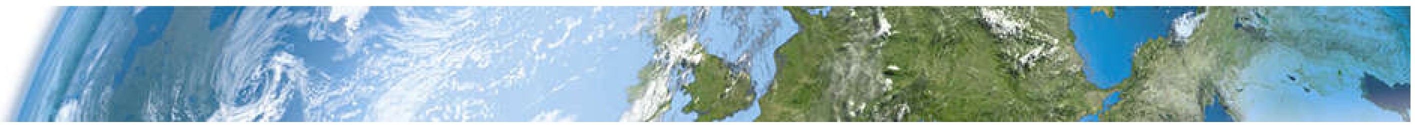
gas ⟷ friction ⟷ dust

plasma ⟷ charge ⟷ dust

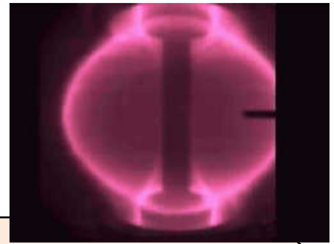
dust

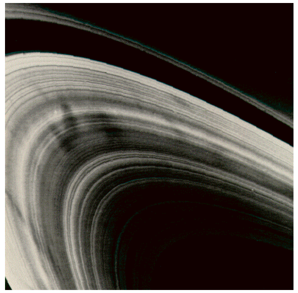
liquid

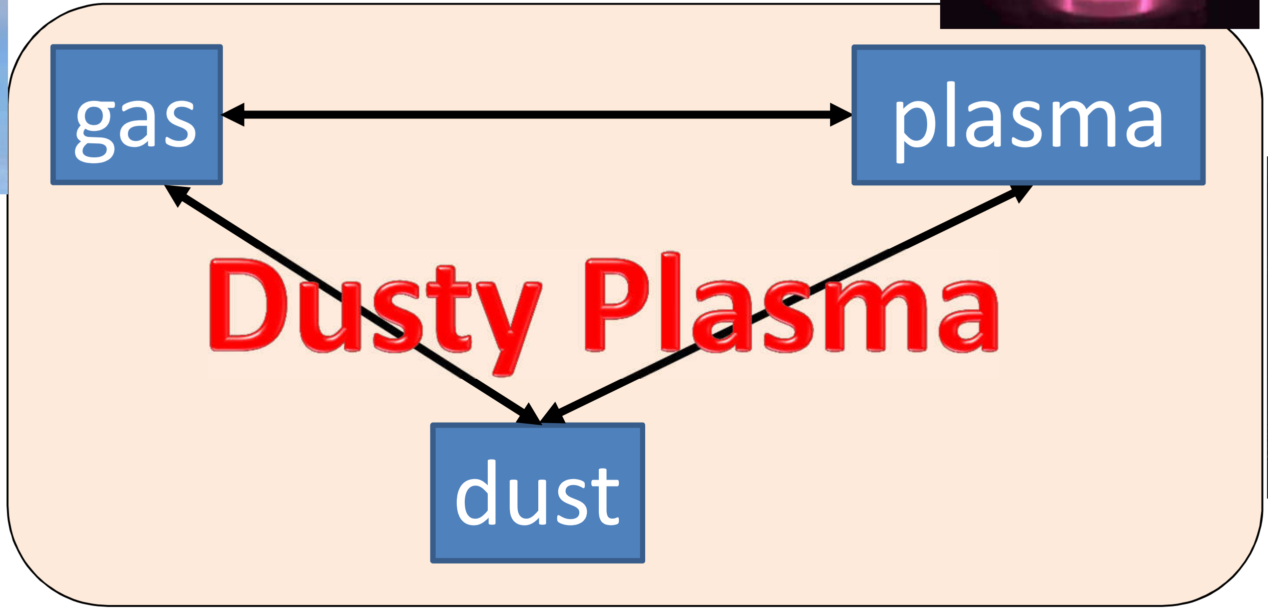
solid



What is a Dusty Plasma?







liquid

solid

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Dusty Plasma History
First observation in lab

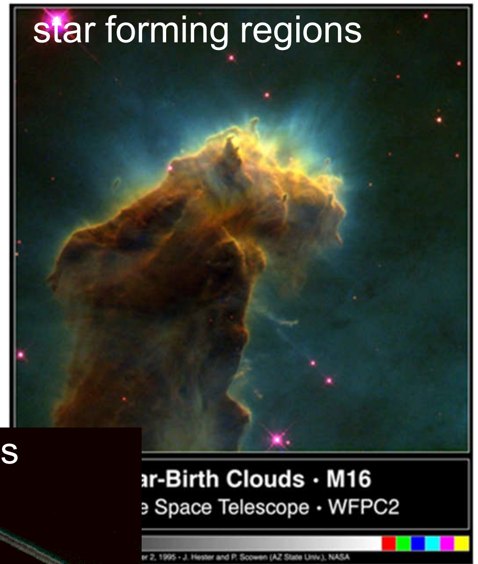
The first observations of dust in a laboratory plasma were made by Langmuir. He reported these observations on September 18, 1924 at the Centenary of the Franklin Institute in Philadelphia.

Langmuir, Found and Dittmer, Science, vol. 60, No. 1557, p 392 (1924)

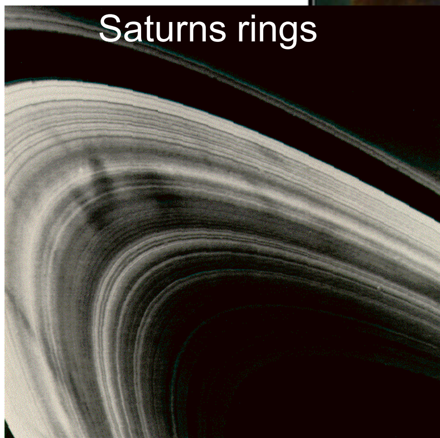
"... we have observed some phenomena of remarkable beauty which may prove to be of theoretical interest."

Dusty Plasma History – Space

- “plasma“ is everywhere in the Universe
- a fraction of this plasma is “dusty“:
  - Galaxies, interstellar clouds, star forming regions, planetary discs, comets, our atmosphere, planetary rings

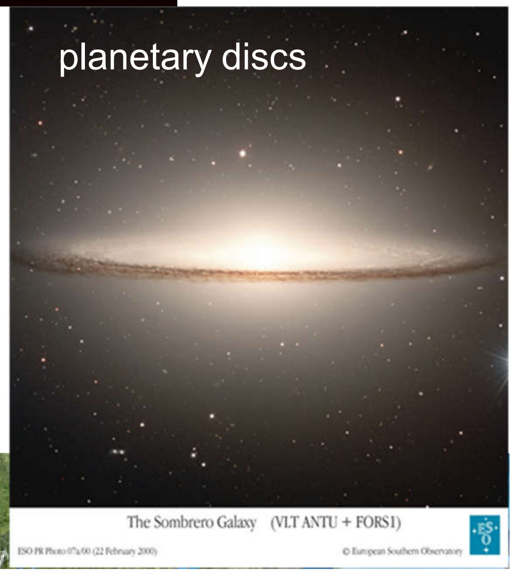


star forming regions


Saturns rings

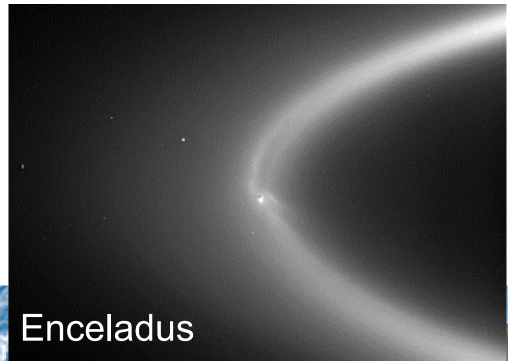

noctiluscent clouds


comets



planetary discs


volcanic eruptions

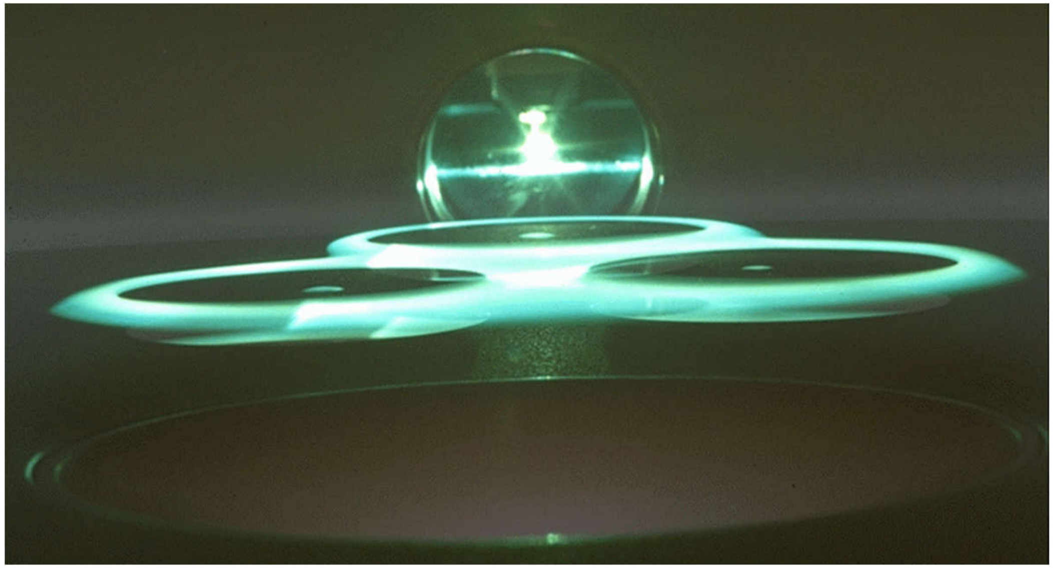

Enceladus

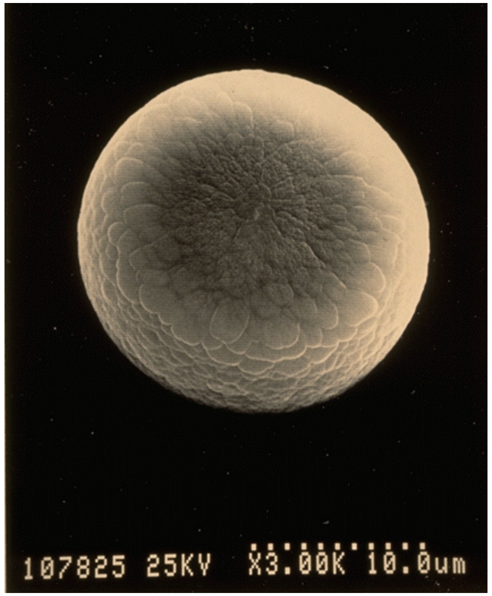
Dust in processing plasmas

Unexpected dust problems in plasma-surface processing : pioneering works

-e.g. PECVD (a-Si:H): **Spears & al , IEEE trans. Plasma Sc. 14, 179, 1986.**

-e.g. etching (SiO_2): **G. Selwyn & al , J. Vac. Sci. Techn. A 7, 2758,1989.**





G.S. Selwyn, Plasma Sources Sci. Tehcnol. 3, 340 (1994).

Images from Gary Selwyn: The original discovery that RF plasmas (etching/deposition) can be appropriate medium for particle growth in the gas phase and particle levitation.

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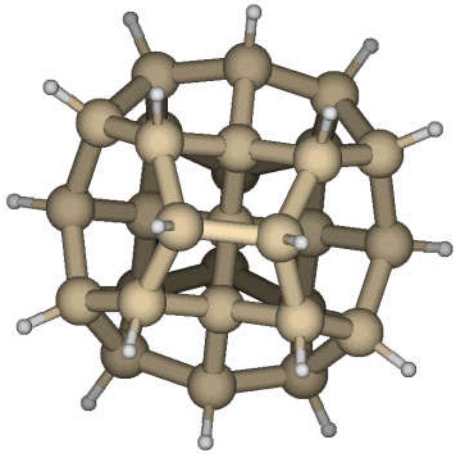
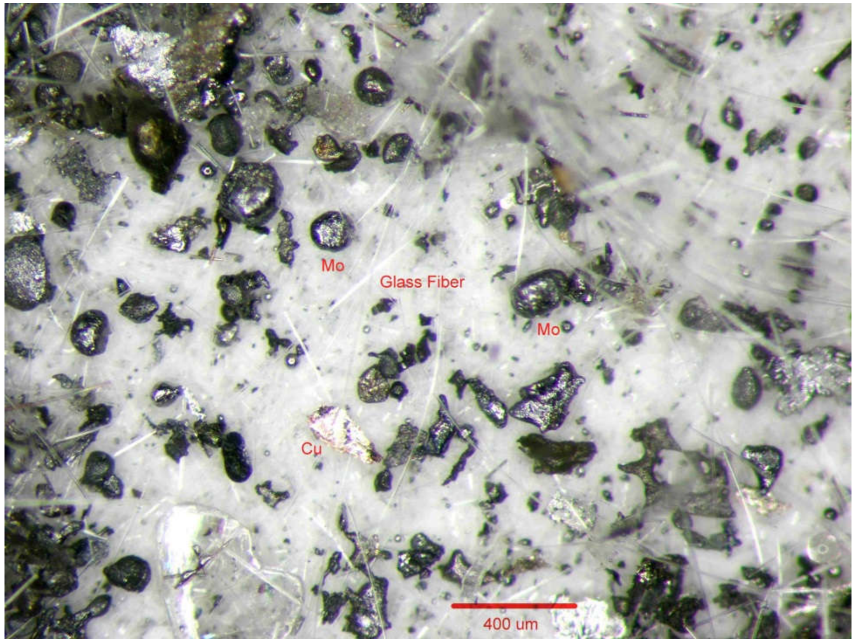
Dust Particles

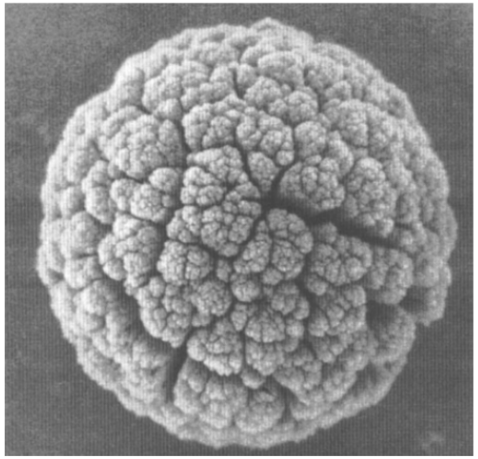
- sizes from large molecules via clusters to mm, typical size µm
- shape: spherical, elipsoidal, rod like, fractal, flake



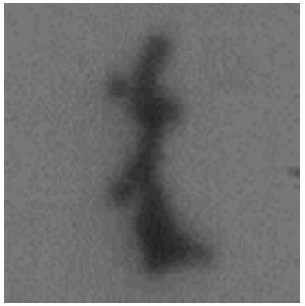
$Si_{29}H_{24}$ cluster under hydrogen bombardment



dust particles in tokamak C Mod



A 650 nm particle grown in an helium rf plasma with carbon electrodes (Boufendi)



Agglomerate of 9µm MF particles with gold coating (Davies)

1986 – Coulomb solid in dusty plasma
The idea

Coulomb solid of small particles in plasmas

H. Ikezi
GA Technologies Inc., P. O. Box 85608, San Diego, California 92138

(Received 11 December 1985; accepted 11 March 1986)

Small particles in plasmas can form a coulomb lattice. The conditions for solidification in a laboratory plasma are discussed.

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1994: Discovery of Plasma Crystals in the Lab

VOLUME 73, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1994

Plasma Crystal: Coulomb Crystallization in a Dusty Plasma

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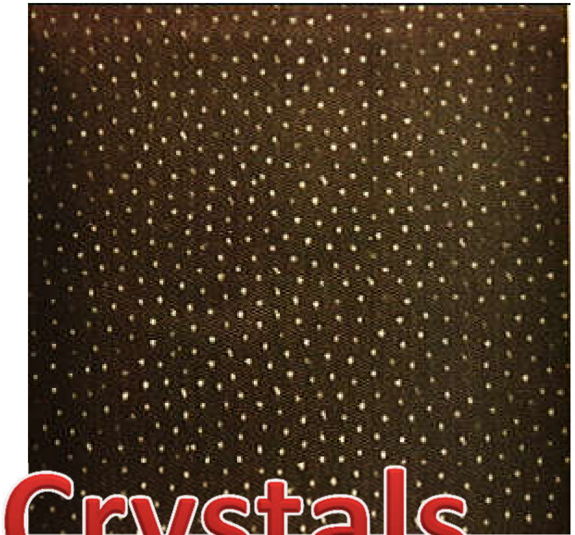
Max-Planck-Institut für Extraterrestrische Physik, 85740 Garching, Germany

J. Goree†
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

B. Feuerbacher and D. Möhlmann
DLR, Institut für Raumsimulation, 51140 Köln, Germany
(Received 25 January 1994)

A macroscopic Coulomb crystal of solid particles in a plasma has been observed. Images of a cloud of 7-μm "dust" particles, which are charged and levitated in a weakly ionized argon plasma, reveal a hexagonal crystal structure. The crystal is visible to the unaided eye. The particles are cooled by neutral gas to 310 K, and their charge is >9800e, corresponding to a Coulomb coupling parameter $\Gamma > 20700$. For such a large Γ value, strongly coupled pl... a the... predi... that the particles should organi... in ... with ...



25 years of Plasma Crystals

Independent discovery in 1994 by 4 groups:

- J. H. Chu and Lin I, Phys. Rev. Lett. **72**, 4009 (1994).
- H. Thomas, G. E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, and D. Möhlmann, Phys. Rev. Lett. **73**, 652 (1994).
- Y. Hayashi and K. Tachibana, Jpn. J. Appl. Phys. **33**, L804 (1994).
- A. Melzer, T. Trottenberg, and A. Piel, Phys. Lett. A **191**, 301 (1994).

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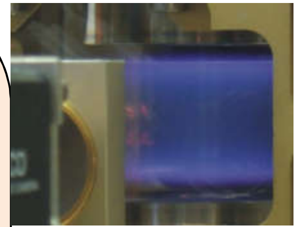
Dusty → Complex Plasma?

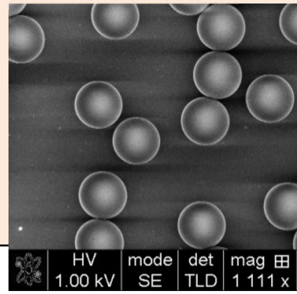


gas

cold plasma

Complex Plasma

microparticles



liquid

solid

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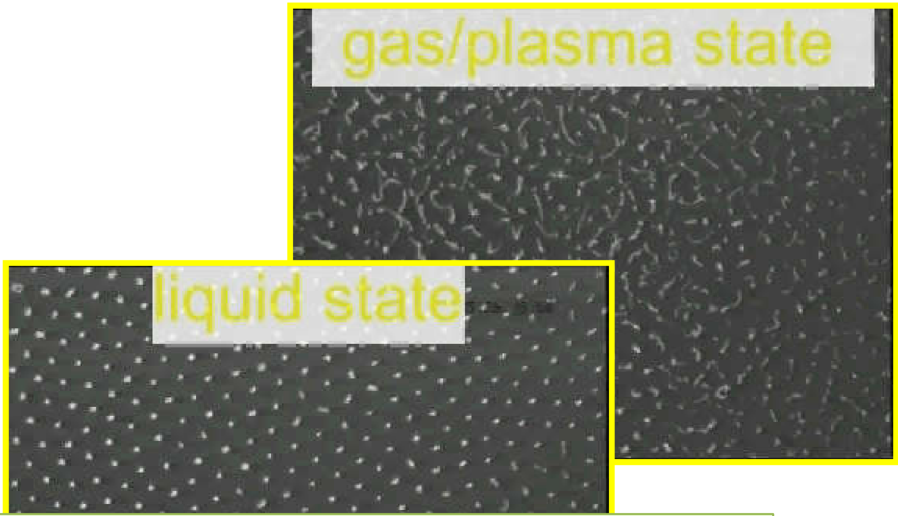
Complex Plasmas

Complex plasmas provide a new experimental approach for fundamental studies of strong coupling phenomena – “fully resolved dynamics at the individual particle level”.

- Particles individually visible
- Atomistic dynamics virtually undamped
- Systems up to 10^9 particles
- Classical system for liquids
- Classical system for crystals



... but gravity disturbs fundamental investigations

1996

Multi-scale research approach

"Microscopic" scale

Plasma-particle interactions

- Particle charging
- Plasma screening
- Plasma absorption on the particles
- Charge fluctuations
- Surface physics/chemistry
- Plasma flows and resulting forces
- Other forces (thermophoresis, polarization, radiation)
- etc.

Plasma physics, astrophysical plasmas, fusion research, technological applications

"Macroscopic" scale

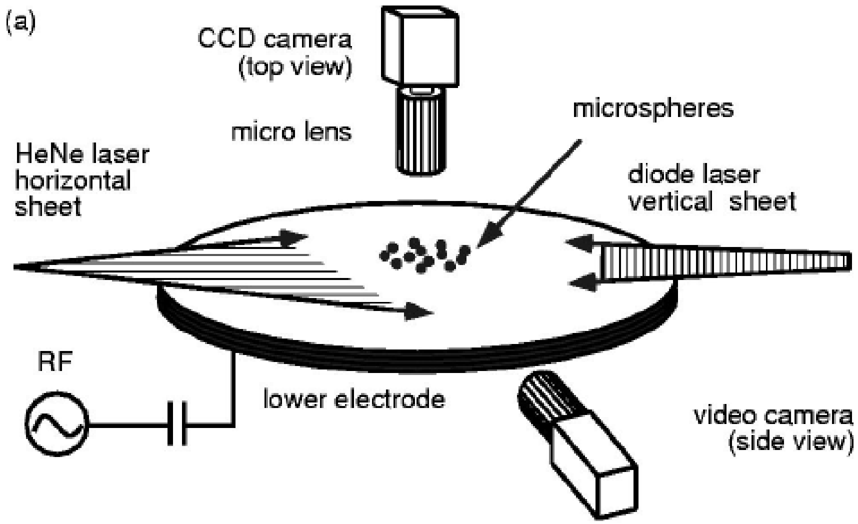
Particle-particle interactions

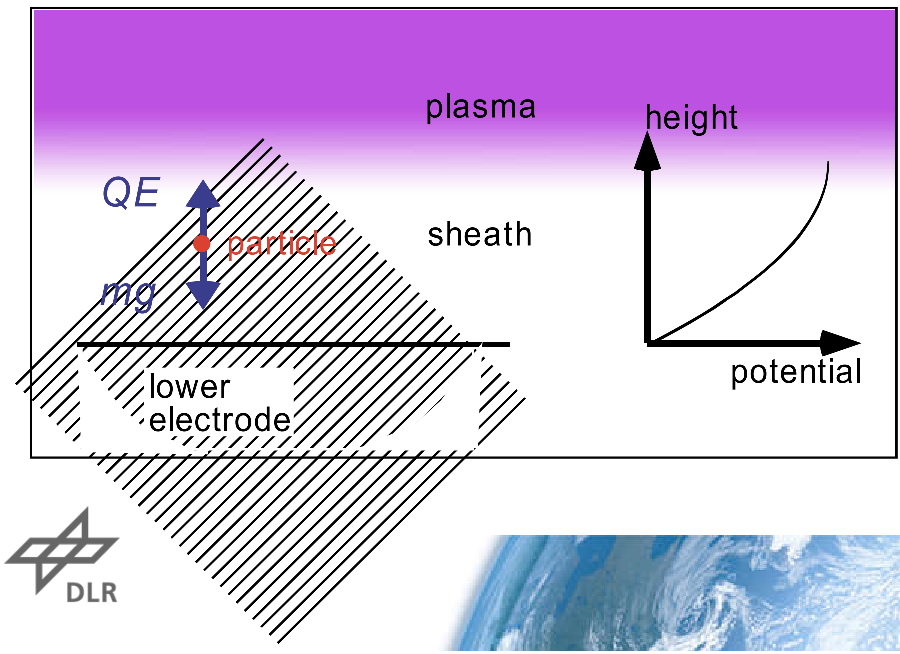
- Collective effects
- Plasma mediated (wakes, shadowing) interactions
- Thermodynamic properties
- Phase transitions
- Critical phenomena
- Transport properties
- Wave phenomena
- etc.

Strongly coupled systems, soft condensed matter, material science, phase transitions

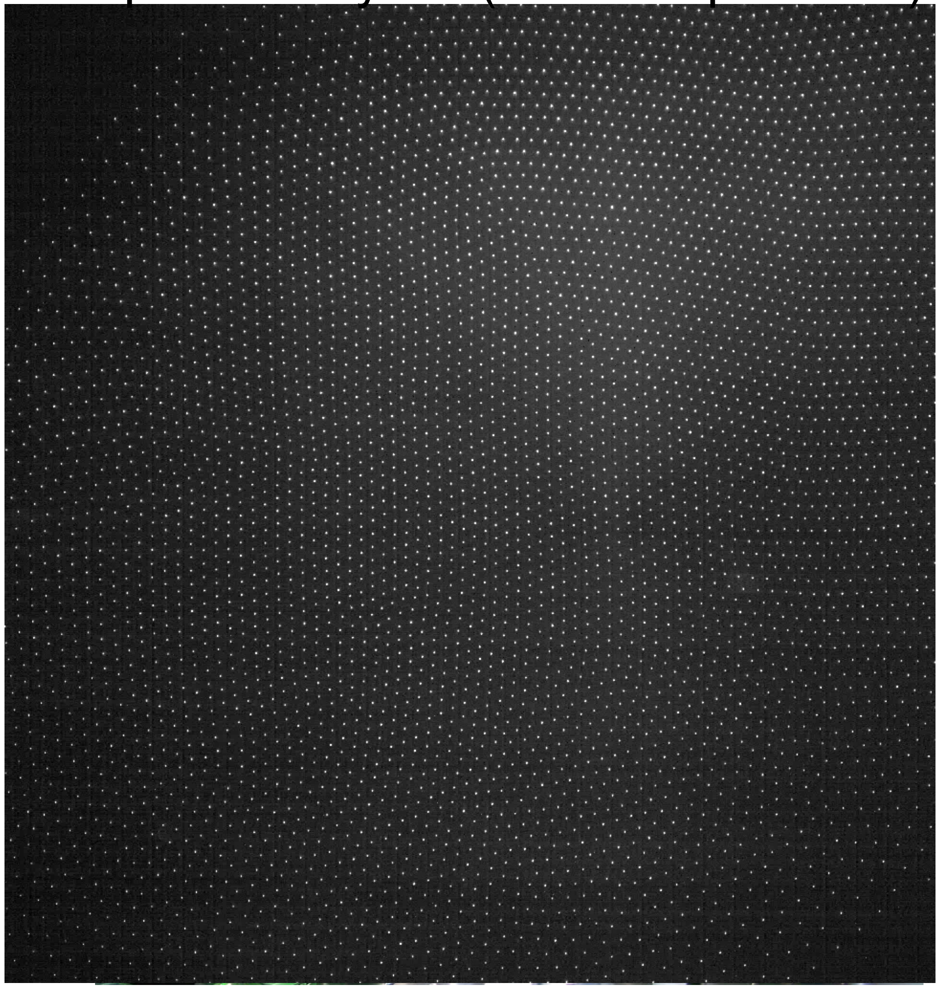
Experiments in the Laboratory

2-D Set-up (Earth Laboratory)





2-D plasma crystal (>> 5000 particles)



GEC-RF Reference Cell

Experiments on 2-D systems

- Phonons excited by particle thermal motion

  S. Nunomura *et al.*, Phys. Rev. Lett. (2002)

- Dislocations generated by excessive shear stress

  V. Nosenko *et al.*, Phys. Rev. Lett. (2007)

- Recrystallization of a 2D Plasma Crystal

  C. Knapek *et al.*, Phys. Rev. Lett. (2007)

- Mach cones caused by extra particles beneath the lattice or laser excitation

  D. Samsonov *et al.*, Phys. Rev. Lett. (1999)

  A. Melzer et al., Phys. Rev. Lett. (2002)

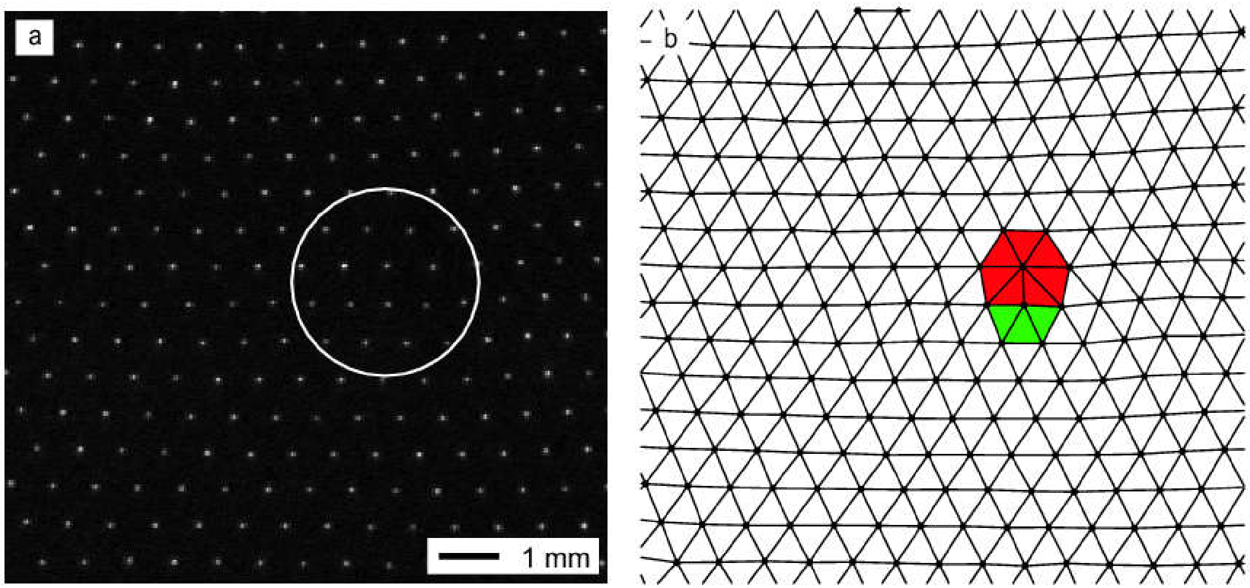
- Mode-coupling instability due to plasma wakes

  L. Couëdel *et al.*, Phys. Rev. Lett. (2010)

Science Question: Limiting speed of dislocations

- Controversial subject: The common wisdom was that a gliding edge dislocation cannot surpass the sound speed of shear waves C_T, as the energy radiated by a dislocation becomes infinite at C_T.

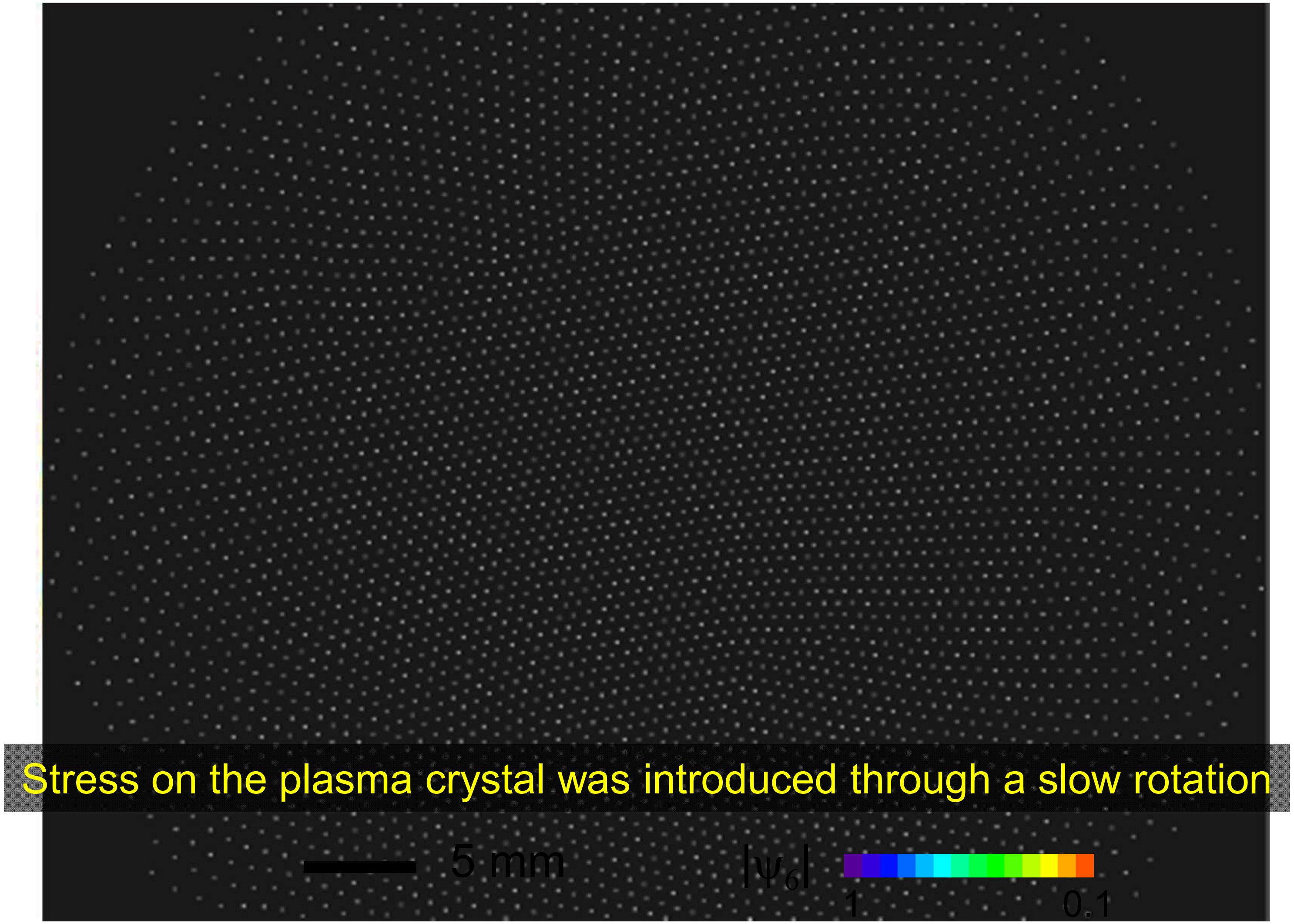
- Ho … n 1949)
  tha … 2 C_T
  wi…



- Su … ined in
  ato … ce 1999).

- Ho…

“Gliding dislocations”in 2D plasma crystals



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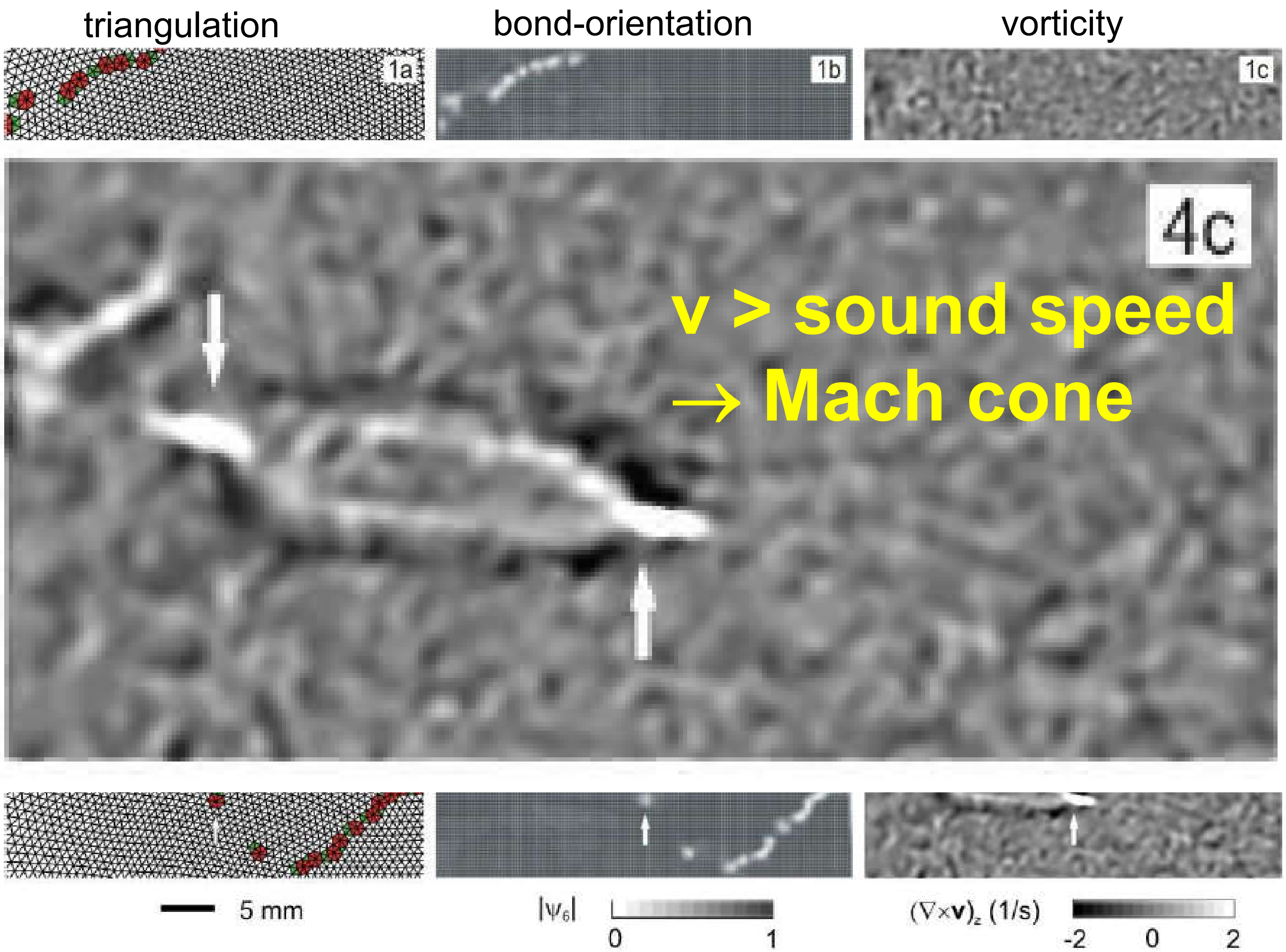
Dislocations observed at kinetic level



V. Nosenko, S. Zhdanov, and G. Morfill, PRL 2007

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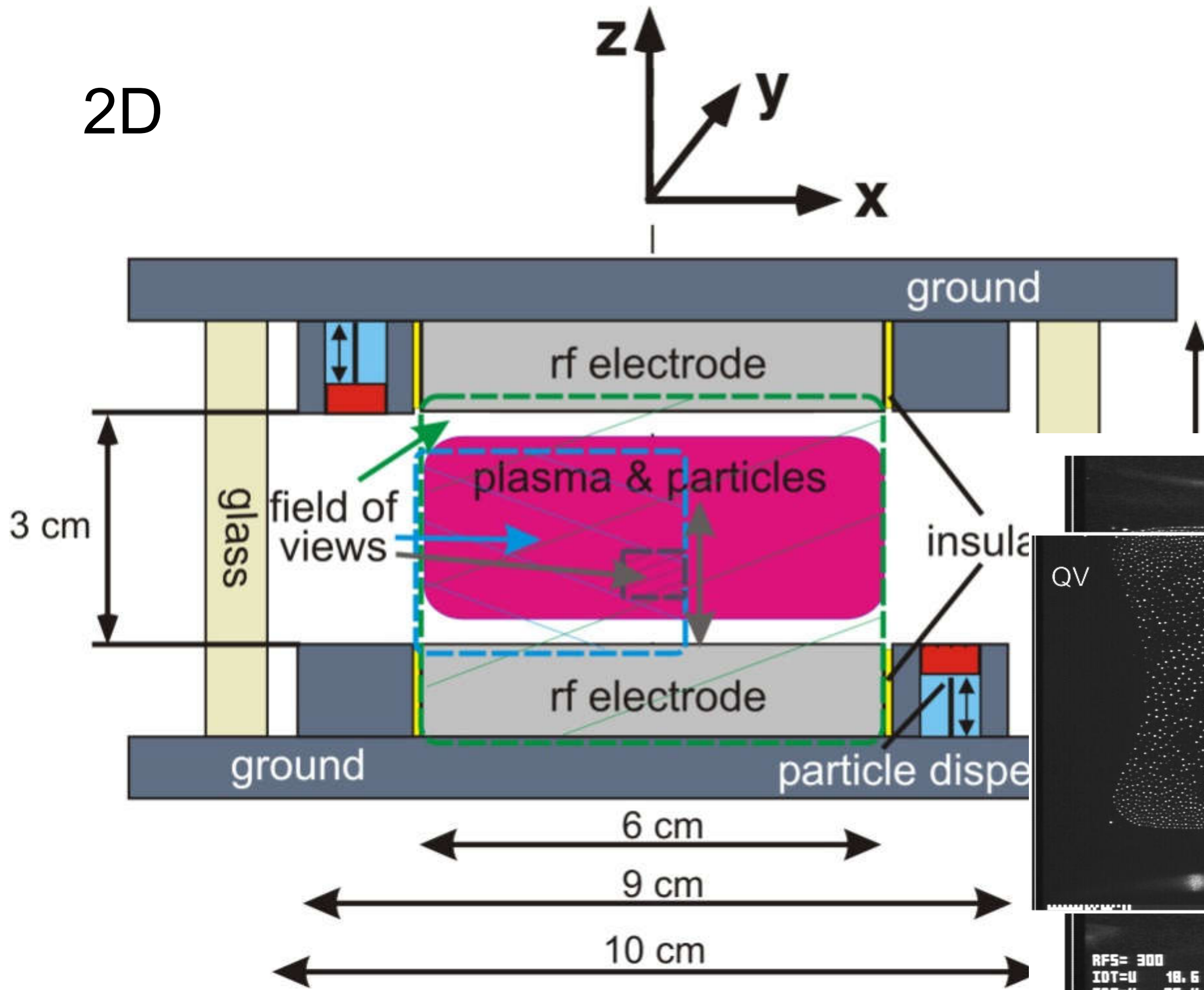
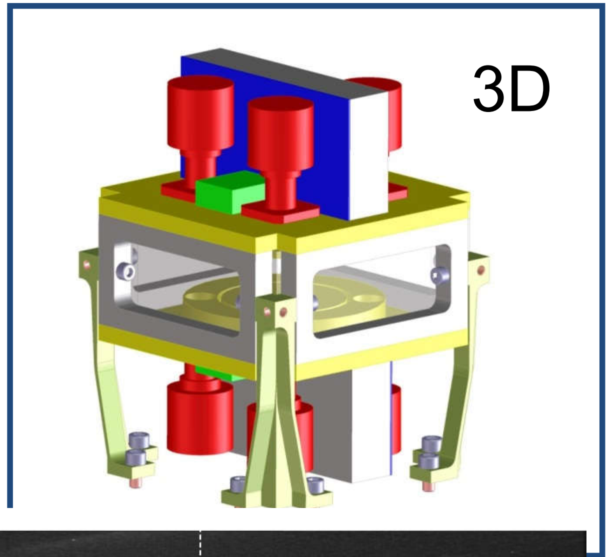
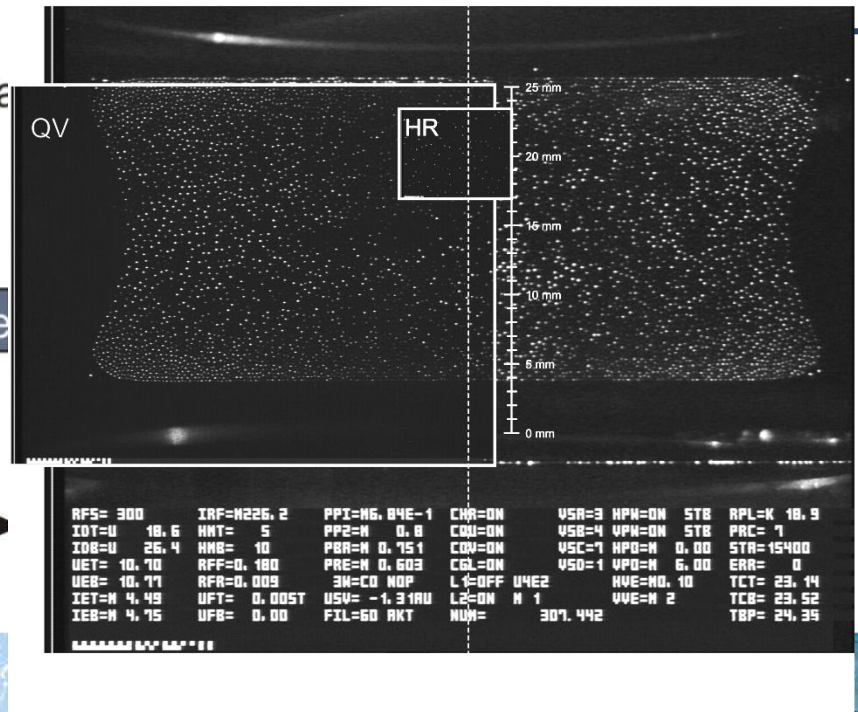
3-D Set-up (Earth and Space Lab)

2D







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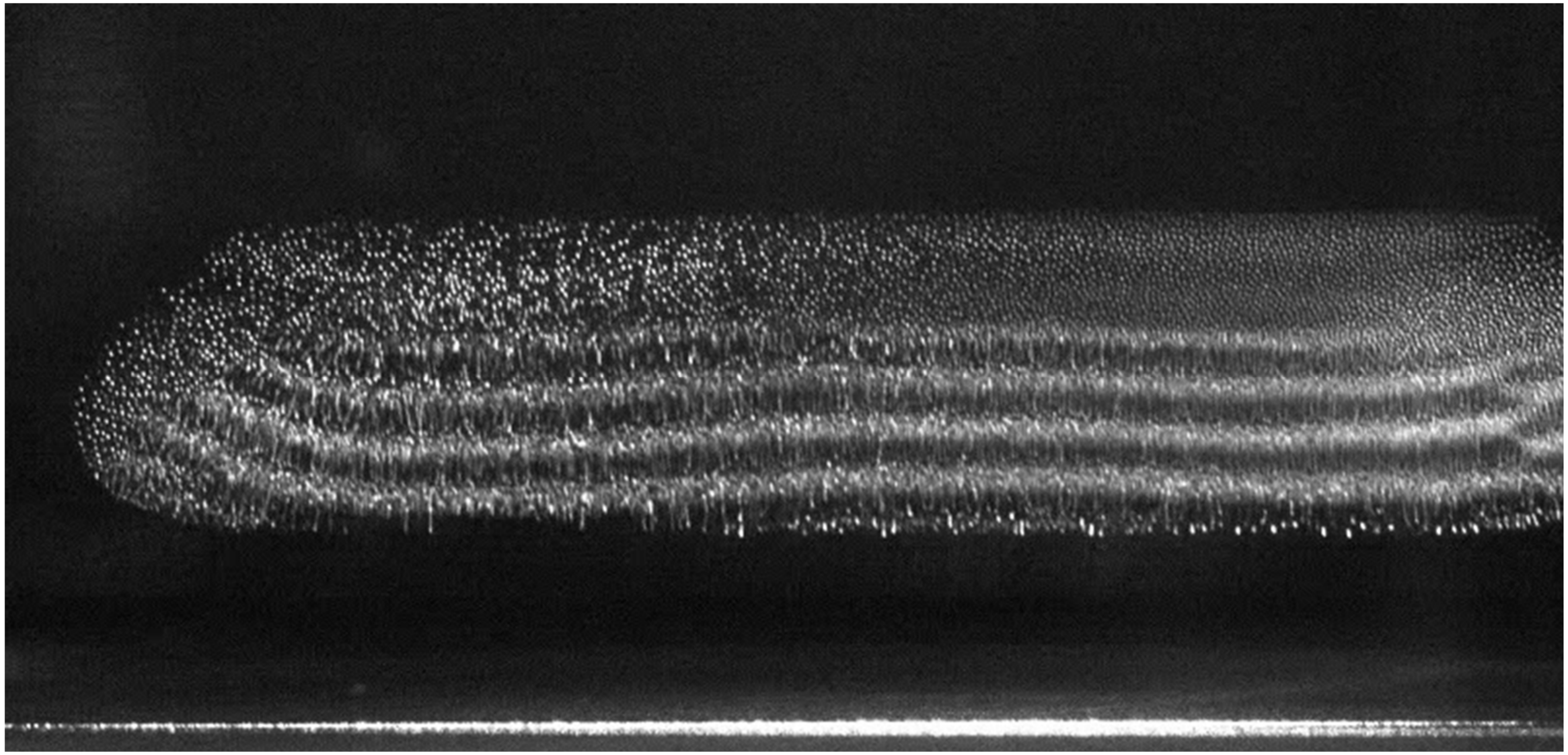
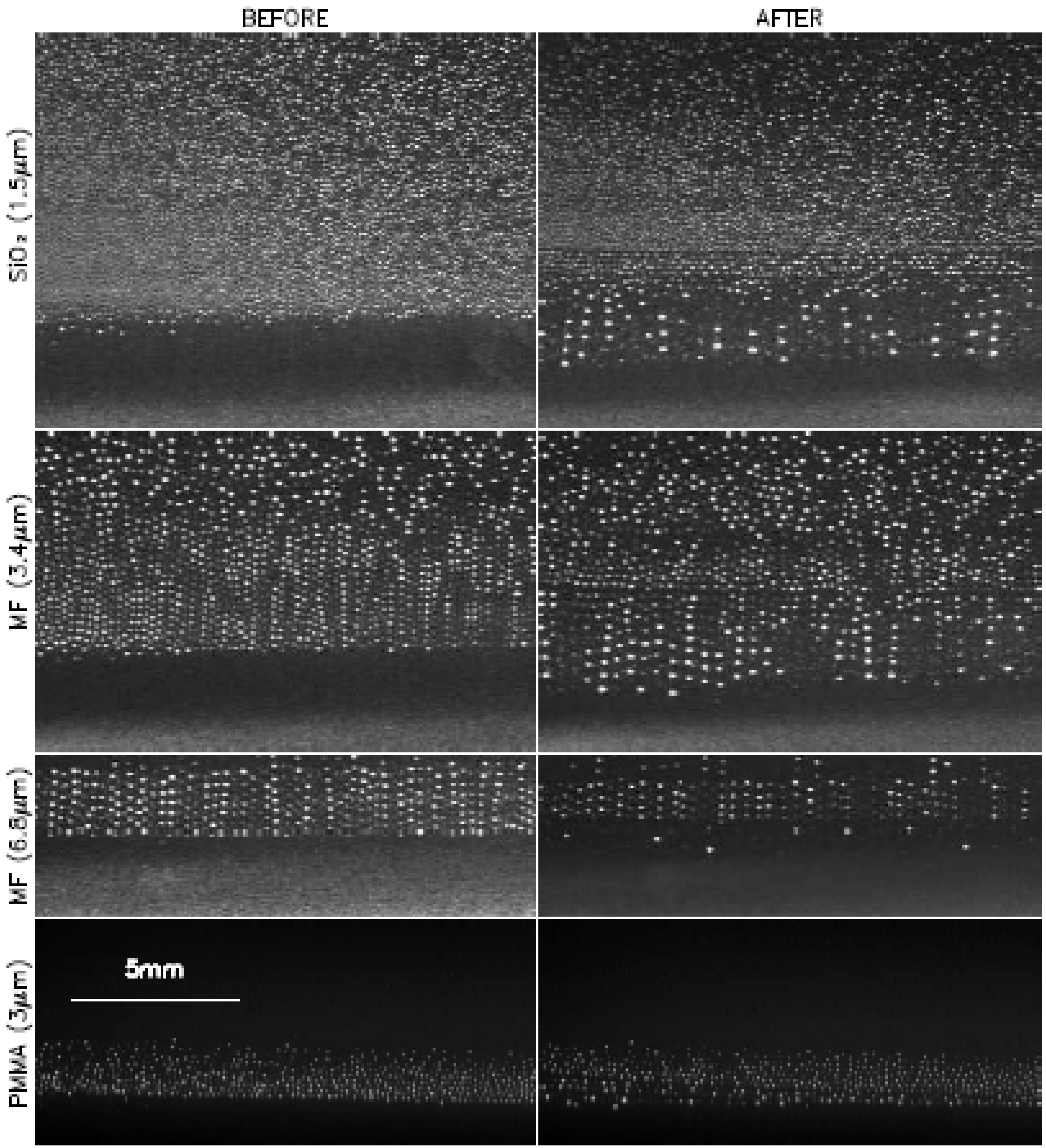
Dust Agglomeration in Waves



MF particles, 1.28 µm diameter

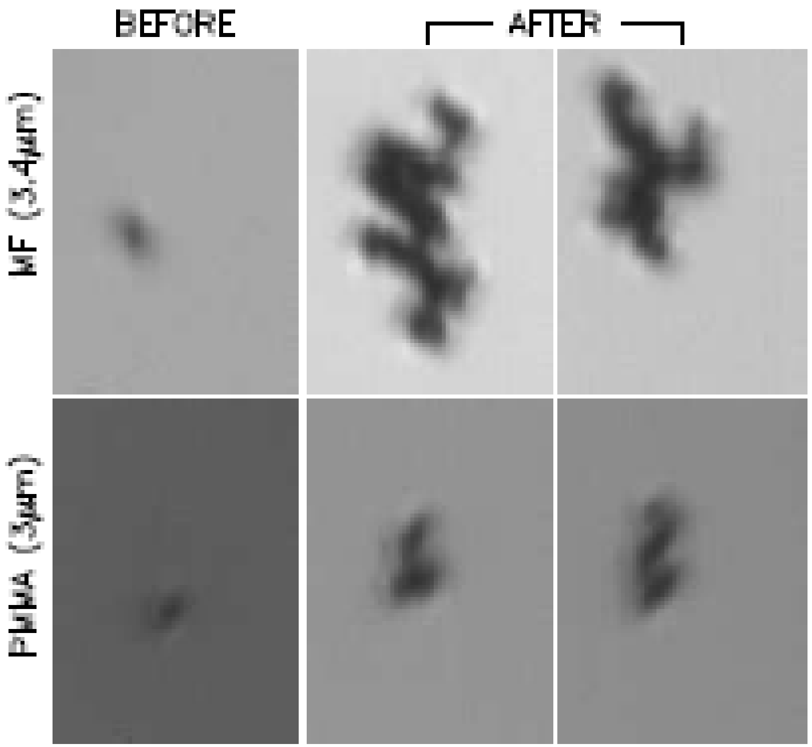
Schwabe, et al., PRL 2007

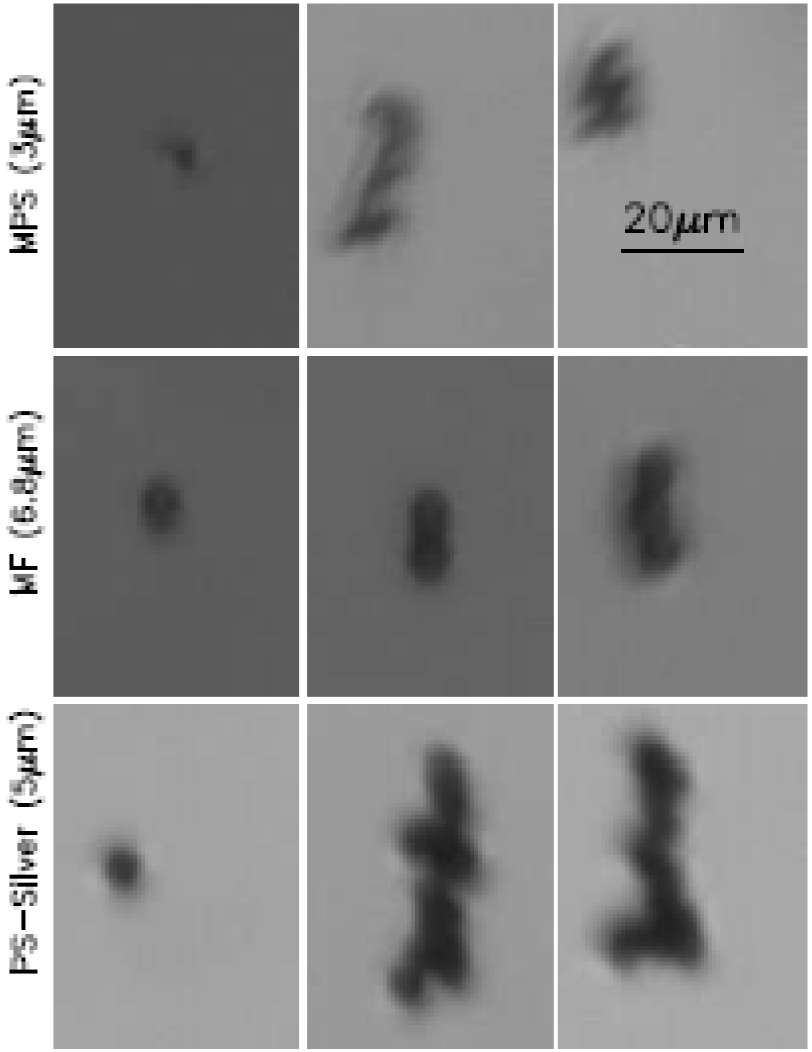
Dust Agglomeration in Waves



Du, et al., NJP 2010

Dust Agglomeration in Waves





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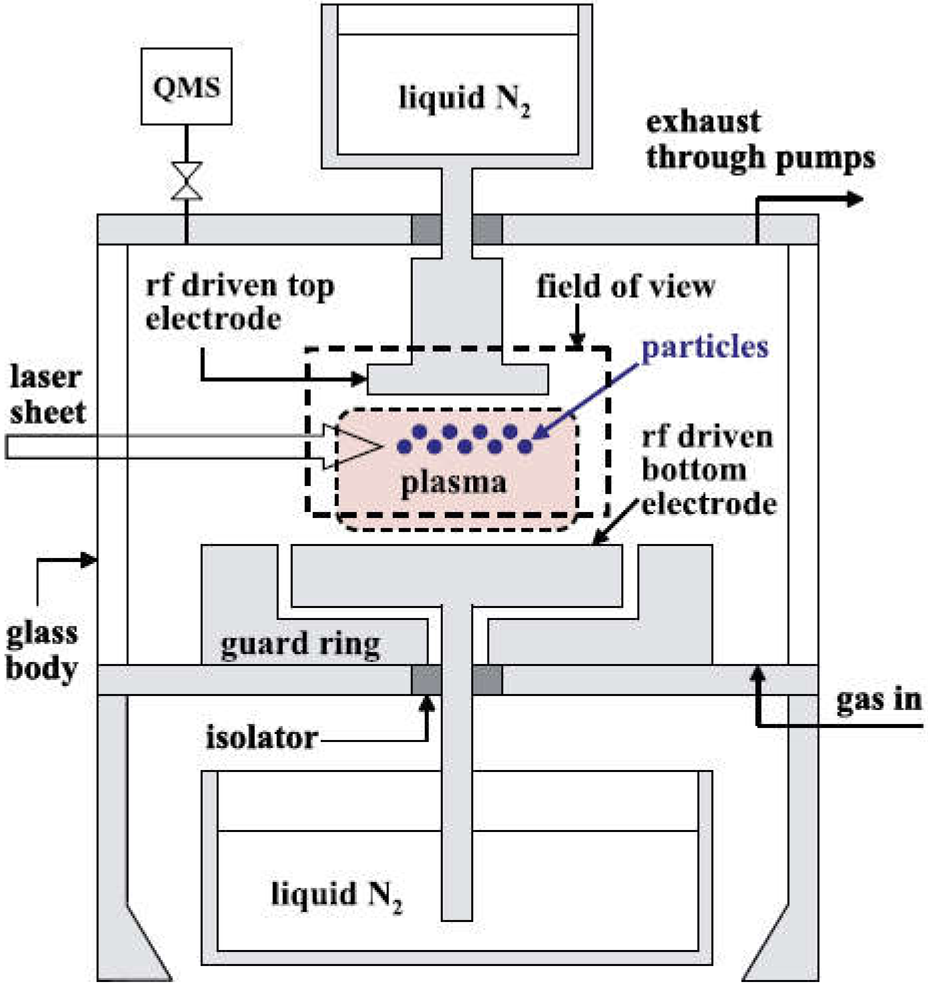
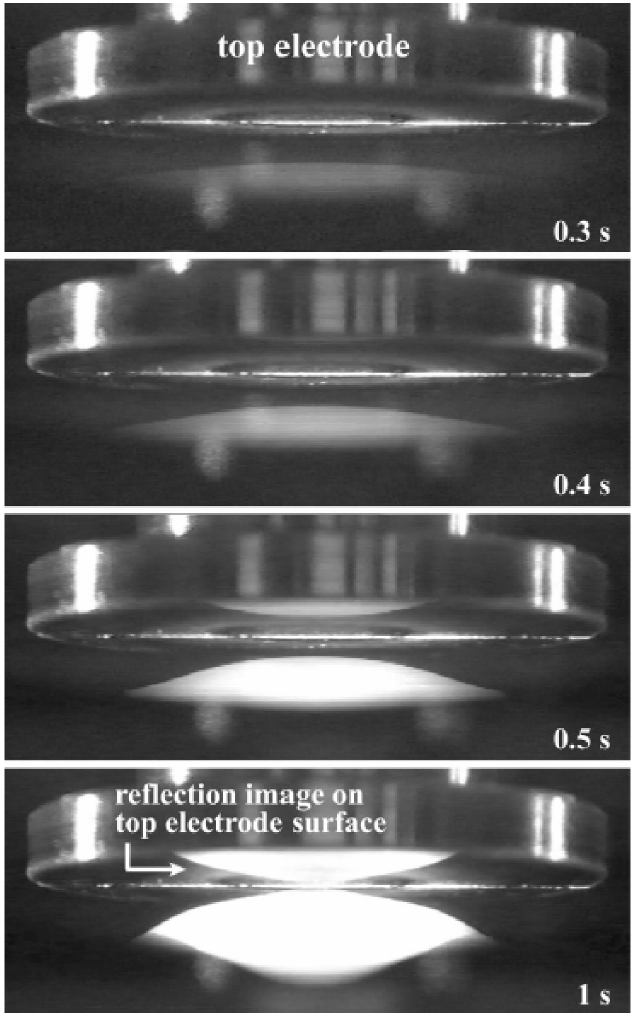
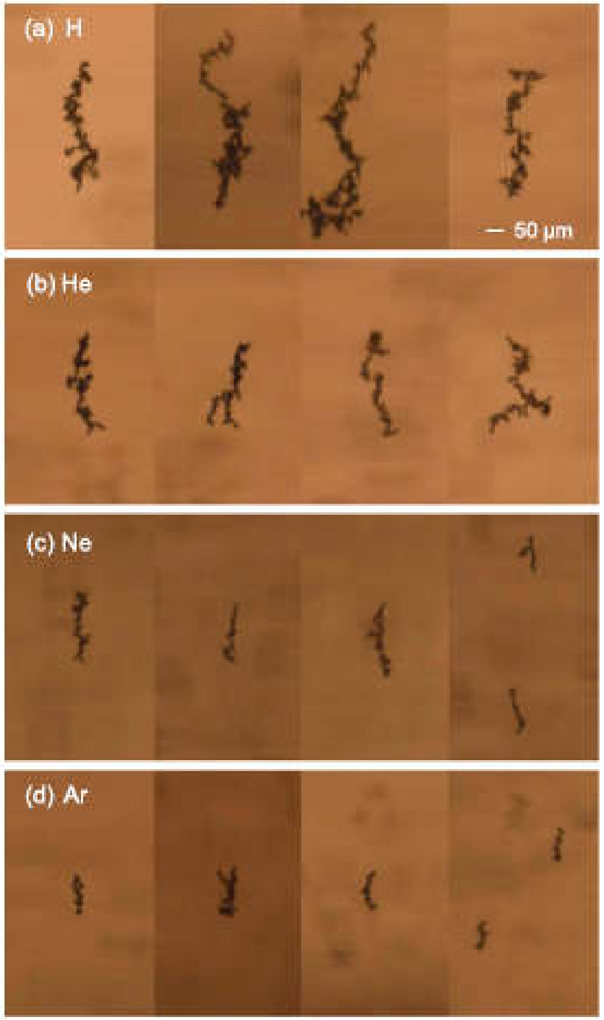
Ice particle growth in D_2-O_2 plasma

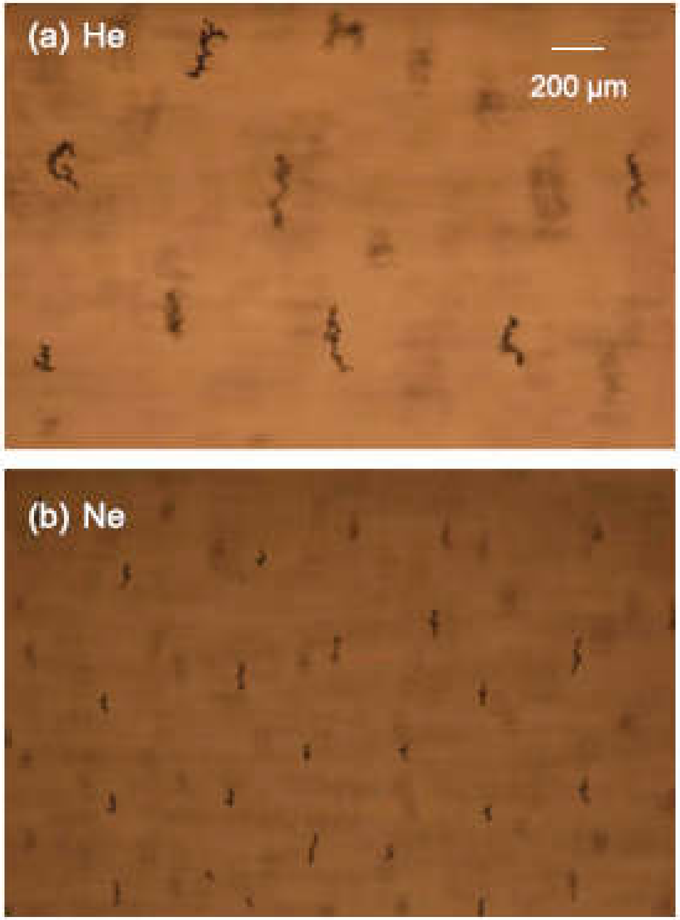




Shimitsu al., JGR 2010

Ice particle growth in plasma with H_2O





Chai et al., APJ 2015

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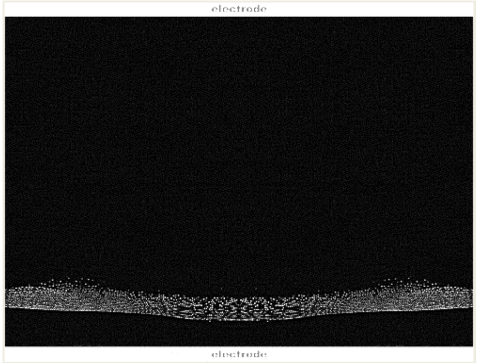
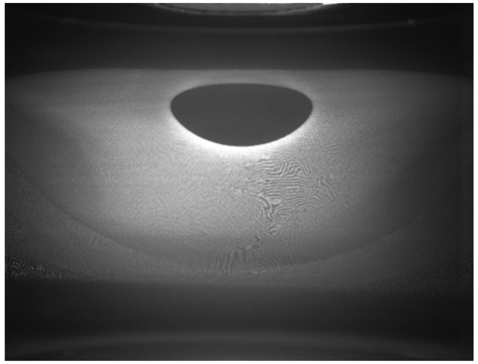
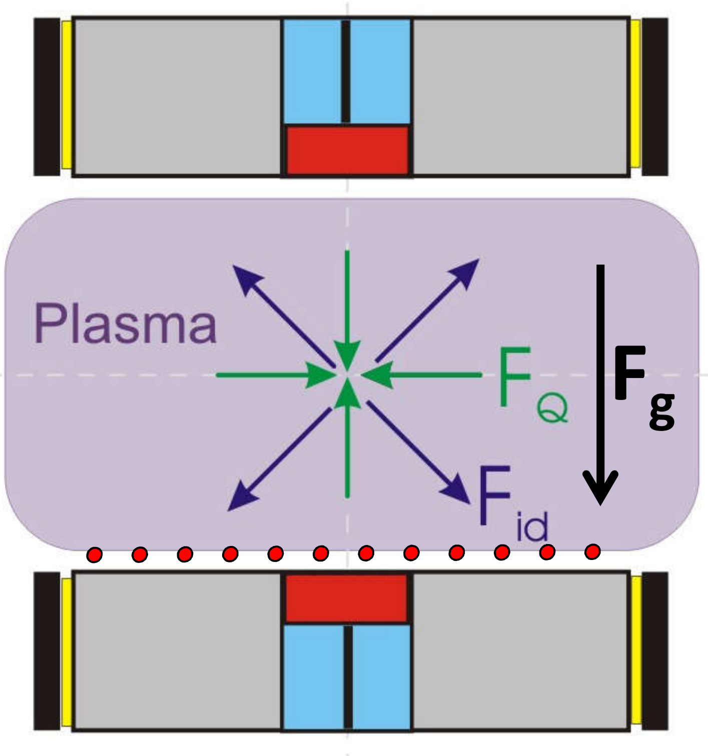
Gravity

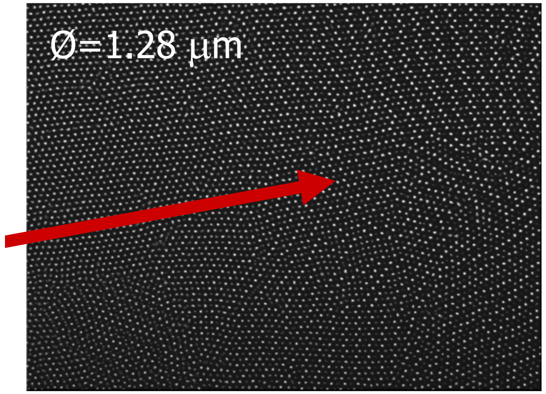


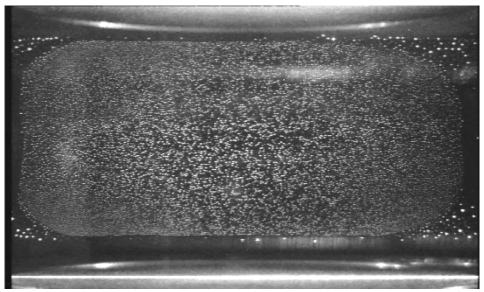
gravity

- Well defined 2D systems can be formed and investigated at the kinetic level (phase transitions, defect propagation, etc.)
- Force-free 3D – systems are not achievable









ess homogeneous
ier
/ dominate the system

How to overcome gravity?

	µ-g Time	µ-g Quality
Drop Tower	~ 4-9 s	very good
Parabolic Flights	20-25 s	ok
Rocket Experiments	6 – 20 min	very good
Space Experiments	Days or Month	very good

Russian-German/European Labs on ISS

Past:
- PKE-Nefedov: 2001 – 2005
- PK-3 Plus: 2006 - 2013

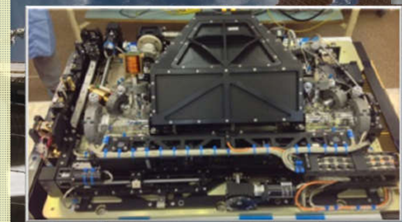
Current:
- PK-4
  - Scientific operation since Oct. 2015
  - Research on fluid and flowing systems

Future:
- Ekoplasma
  - Development of the next generation lab
  - Expanding the accessible parameter range by orders of magnitudes

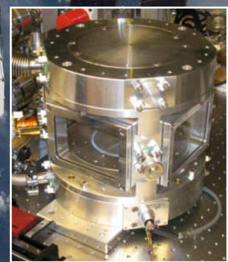
PKE-Nefedov

PK-3 Plus

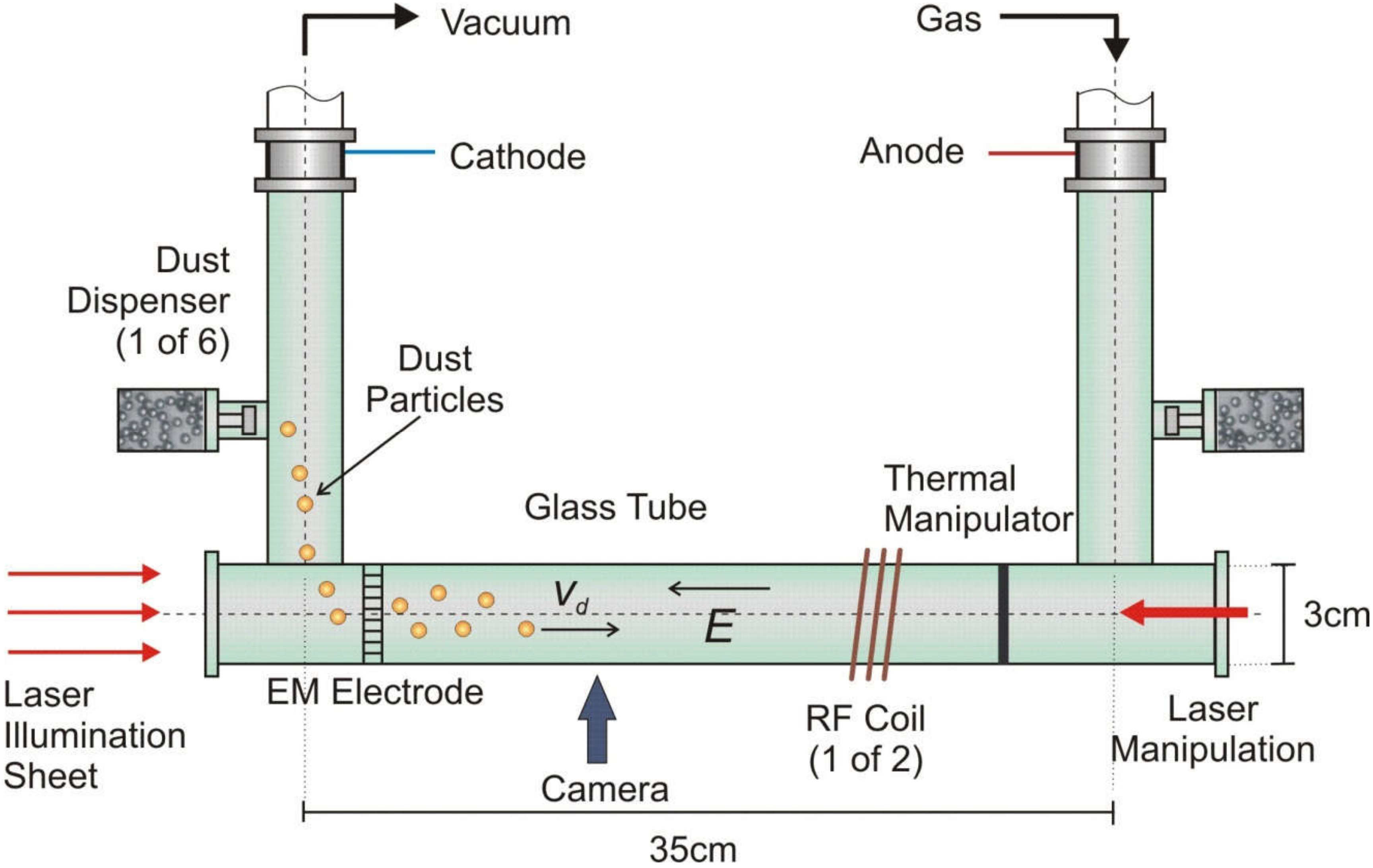
PK-4



Ekoplasma



PK-4 – dc plasma chamber

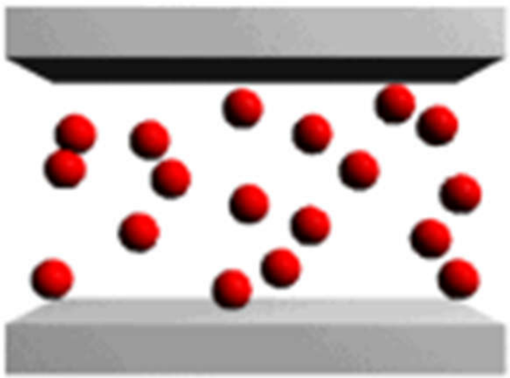


Results from µg experiments

- electrorheological plasmas
- phase separation in binary mixtures

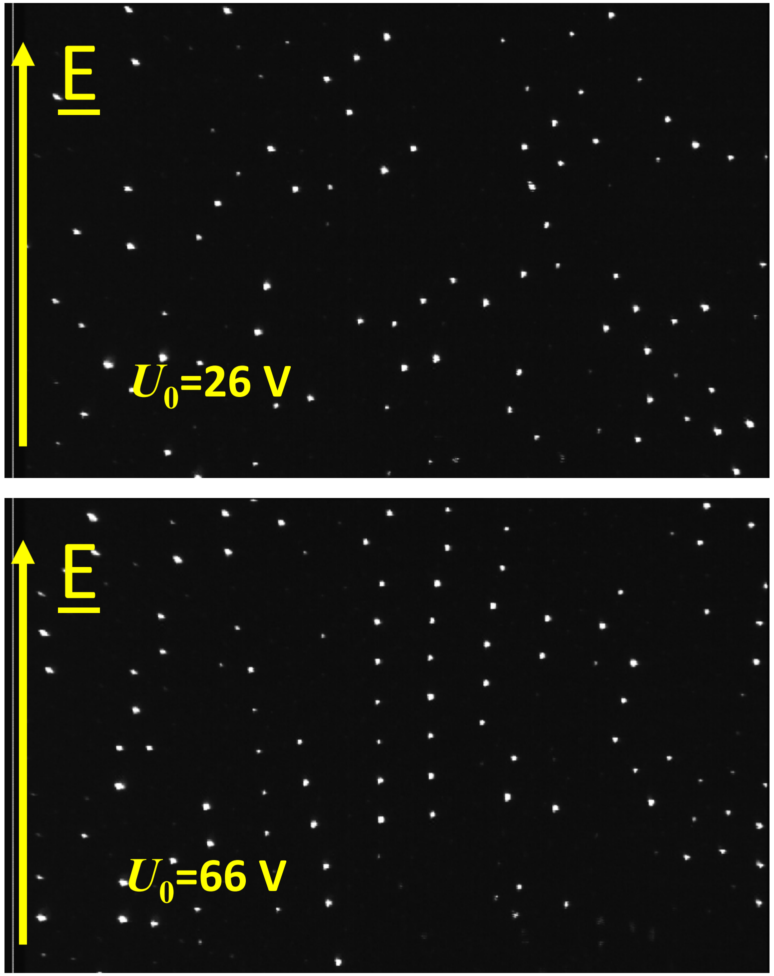
Electrorheological (ER) fluids

- Electro/magnetorheological (ER/MR) fluids are suspensions of microparticles in a non-conducting liquid or gas.
- Interparticle interaction and hence structures formed by microparticles in ER/MR fluids is governed by external electric/magnetic fields.
- ER/MR fluids represent a broad class of viscoelastic media: At low fields they are "normal" fluids. Above a critical field, at low shear stresses ER/MR fluids behave like elastic solids and at high stresses – as viscous liquids.



Electrorheology in Complex Plasmas

- interaction different compared to colloidal fluids
- charge plays an important role
- need for an alternating field

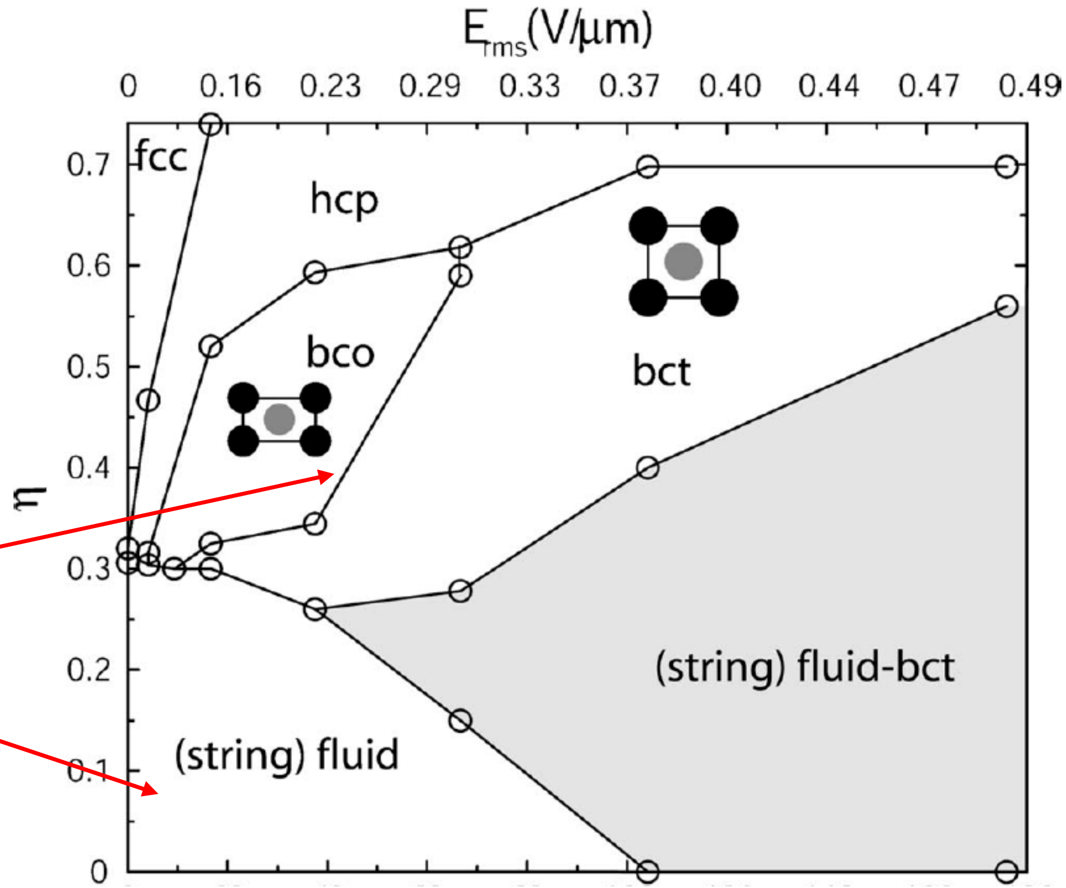


(Ivlev et al., PRL 2008)

Outlook: Phase diagram of ER media

ER media exhibit rich variety of phase states, depending on the packing fraction of particle η and electric field E.

Of particular interest are the bco-bct second-order transition in solids **(Yethiraj & van Blaaderen, Nature 2003)** and the isotropic-to-string transition in fluids at low η and E **(Ivlev et al., PRL 2008).**

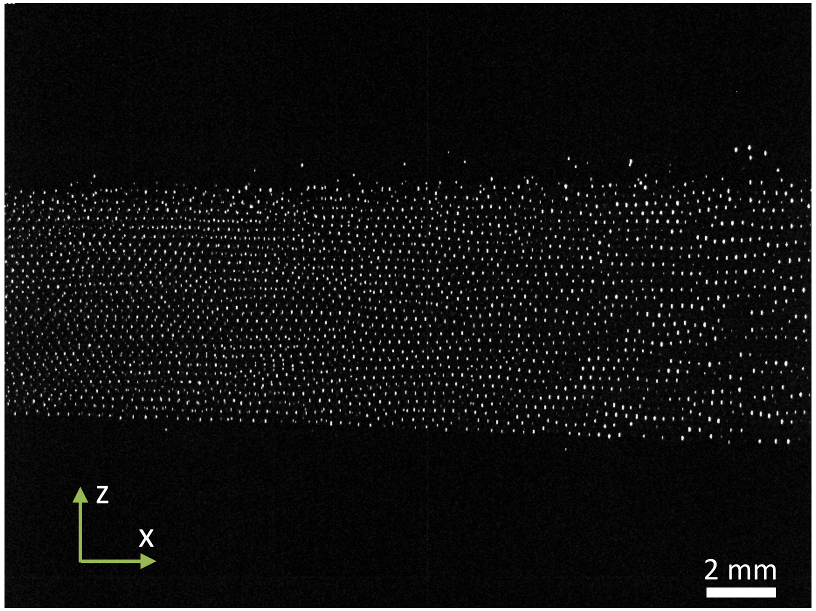


(Hynninen & Dijkstra, PRL 2005)

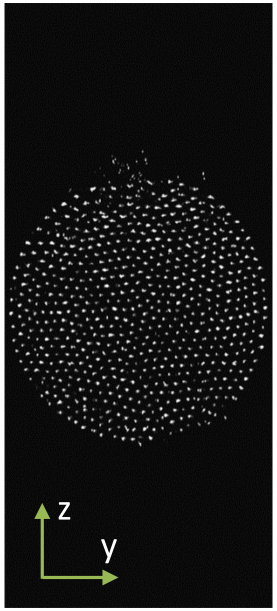
→ PK-4

PK-4 - Formation of ordered structures in ER-Plasmas

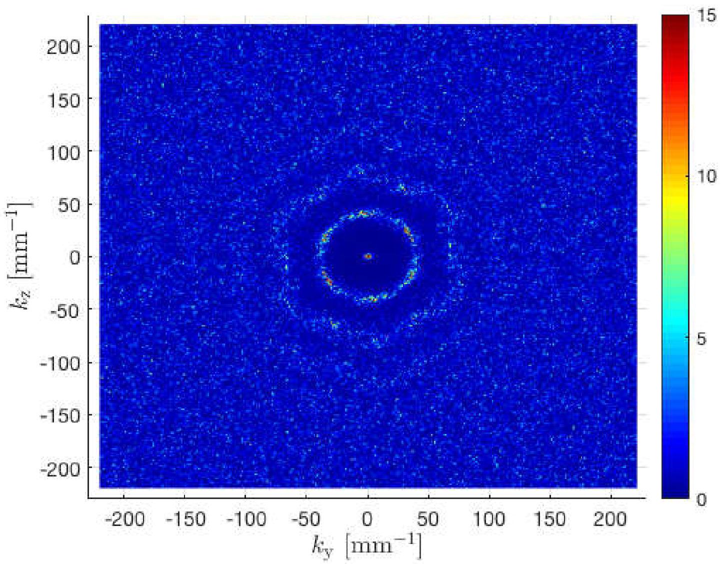
Side view of the suspension



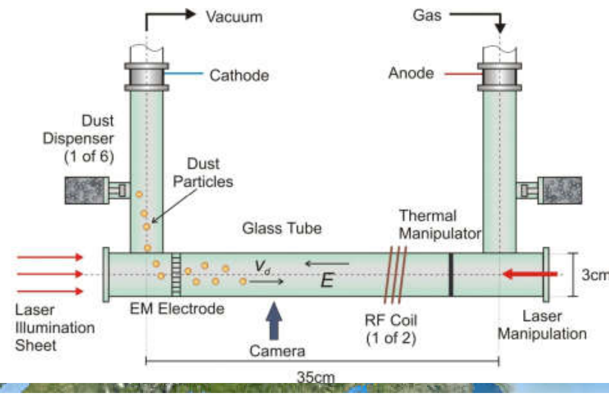
Cross-sectional view



Strucrure factor of the cross-sectional view



argon, 0.2 mbar pressure, symmetric polarity-switching with 0.5 mA current, 500 Hz frequency



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Two-component fluids

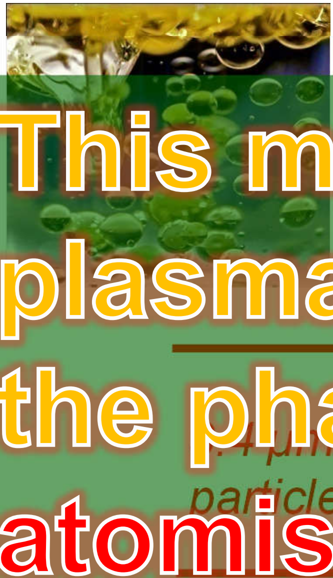
Phase separation

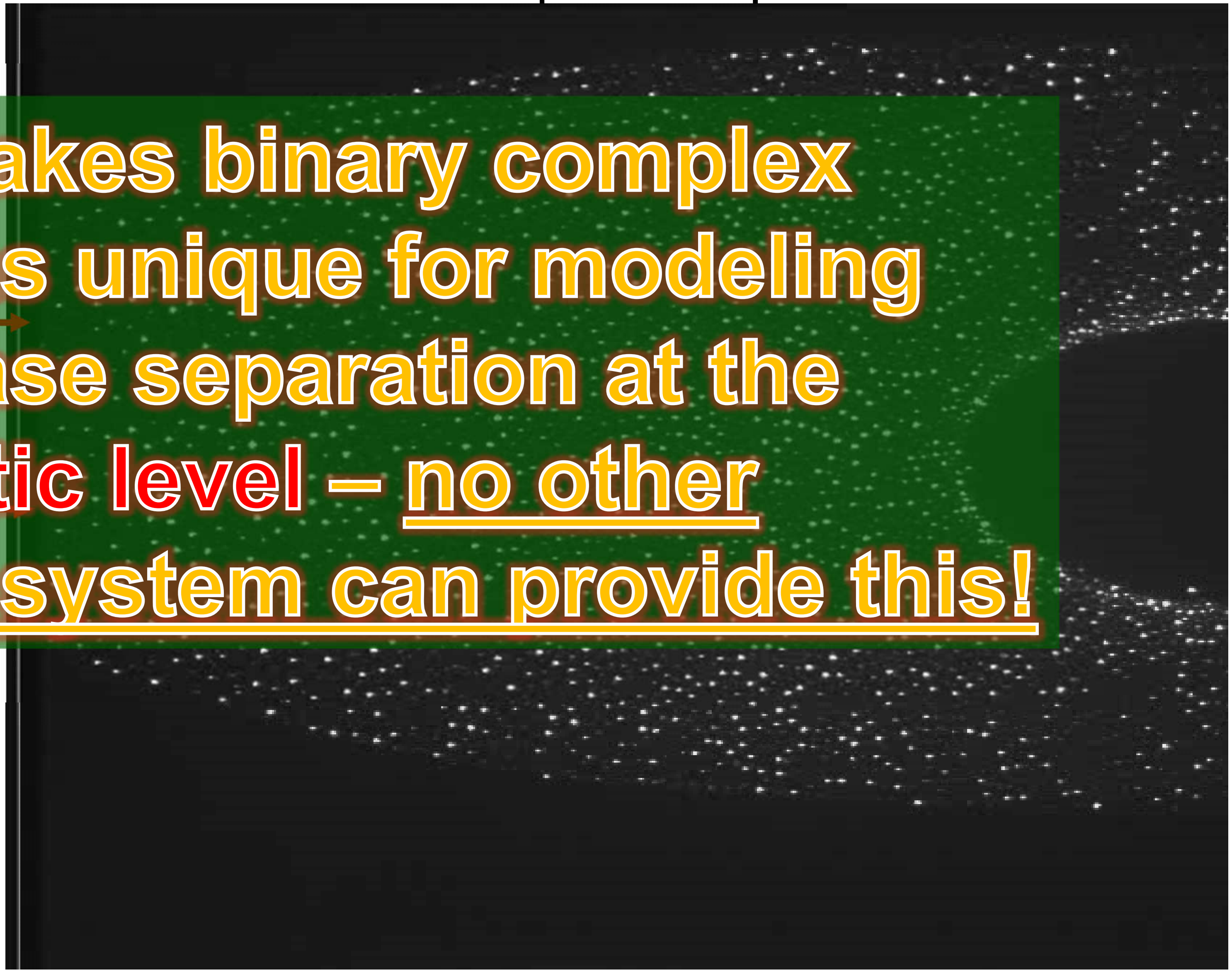
- the „*oil-water problem*“ investigated at the level of individual particles.

- How small can the system be and still separate?
- What is the transition to thermodynamics at the smallness limit?
- What is the role of the interaction potential?

Two component fluids - complex plasmas

First kinetic studies of phase separation





This makes binary complex plasmas unique for modeling the phase separation at the atomistic level – <u>no other known system can provide this!</u>

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Nonadditivity in pair interactions

Equilibrium of binary mixtures is characterized by generalized Berthelot mixing rule,

$$W_{12} = (1+\delta)\sqrt{W_{11}W_{22}}$$

where $W_{ij}(r)$ is the pair interaction energy $(i,j=1,2)$ and
δ is the nonadditivity parameter:

For $\delta > 0$ particles 1 and 2 tend to “avoid“ each other
$\Rightarrow$ phase separation.

For $\delta < 0$ particles 1 and 2 tend to stay close to each other
$\Rightarrow$ mixing.

In complex plasmas, δ is always positive!

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Spinodal line

The spinodal line in the $(\Gamma_1 \kappa^{-2}; x_1)$ space is

$$\frac{\Gamma_1}{\kappa^2} \simeq \frac{1}{48\delta}\left(\frac{1}{x_1} + \frac{1}{\tilde{Z}^2 \ldots}\right)$$

Here $\Gamma_1 = e^2 Z_1^2/T\Delta$ is the coupling par…

parameter, and $x_1 = n_1/\langle n \rangle$ i…

Also, $\widetilde{Z} = Z_2/Z$…

Future perspective: this allows controlled studies of critical point phenomena at the individual particle level for the first time

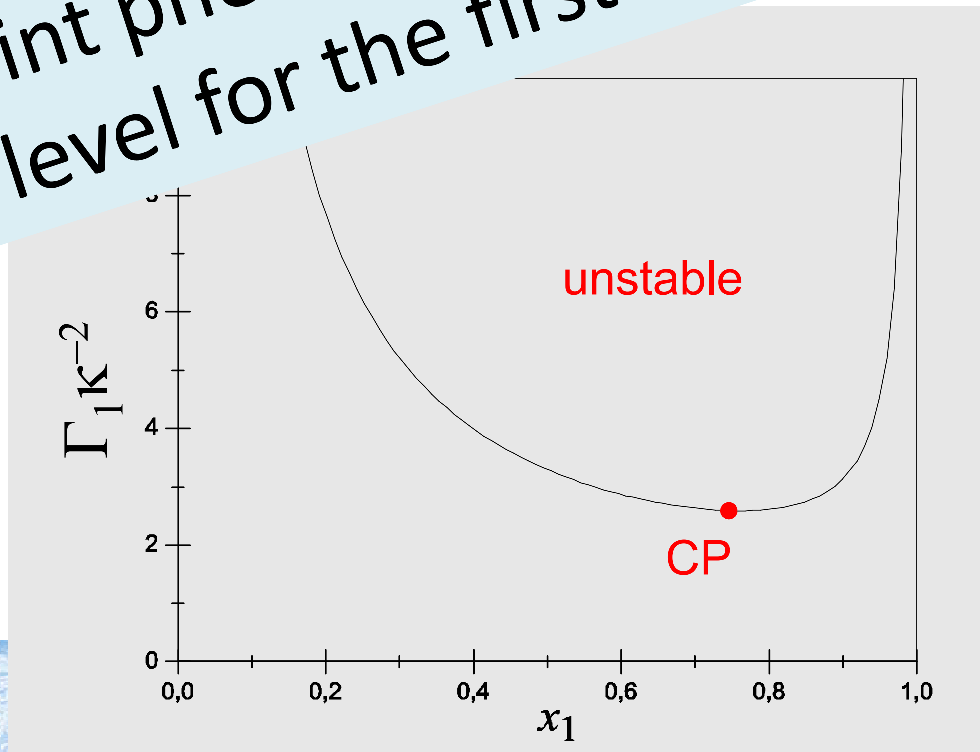
…ve

(… …e critical

p… …ocated at $\Gamma_1 \approx 50$ and

$x_1 \approx 0.8.$

Ivlev et al., EPL 2010



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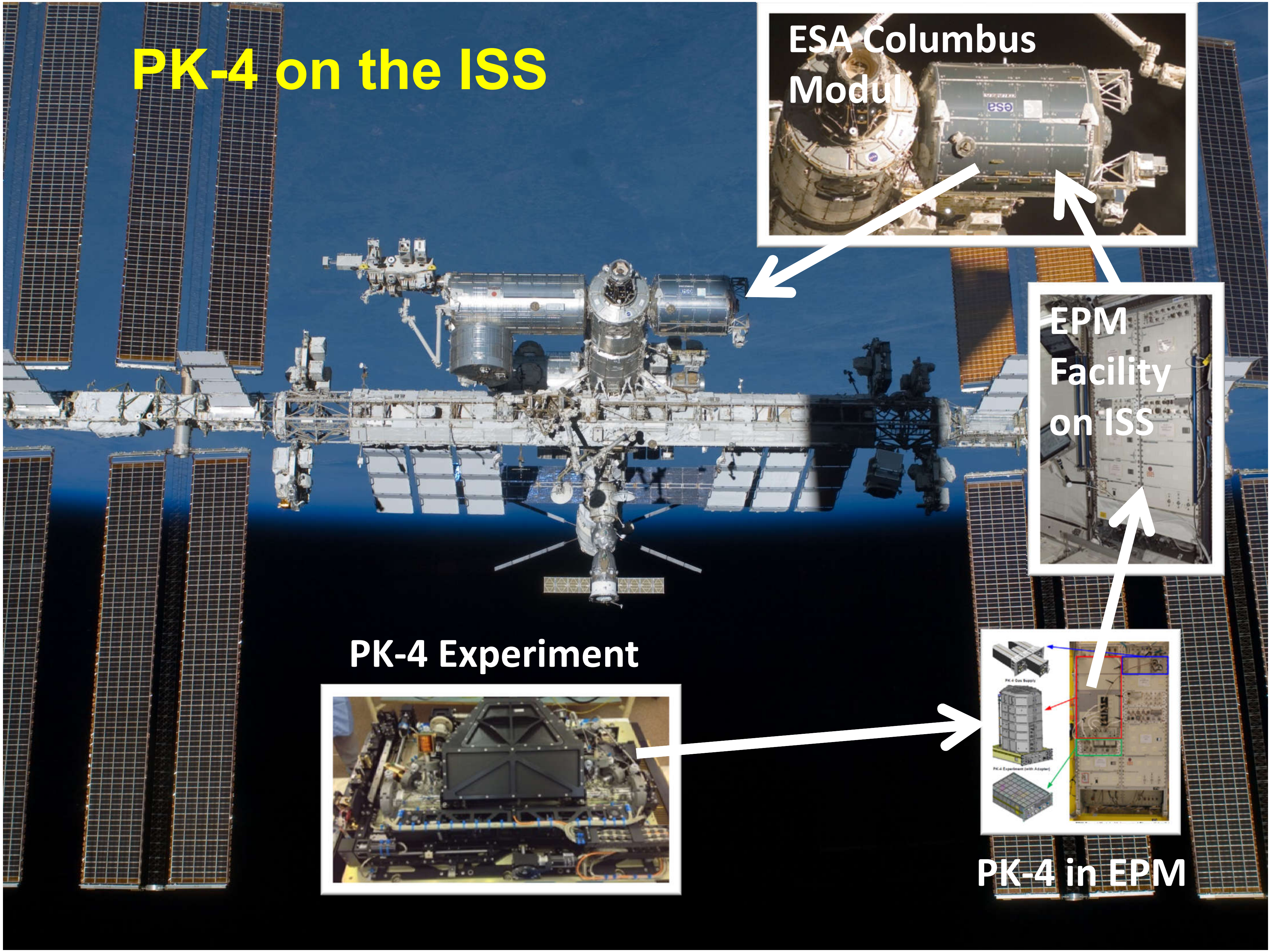
PK-4 on the ISS
ESA Columbus Modul
EPM Facility on ISS
PK-4 Experiment
PK-4 in EPM

PK-4 on the ISS

Laser excited shear flow – experiment from 14.2.2017

- Investigation of a many-body system on the microscopic and kinetic level
- How many particles are needed for collectivity?
- How do macroscopic quantities (e.g. viscosity) develop?

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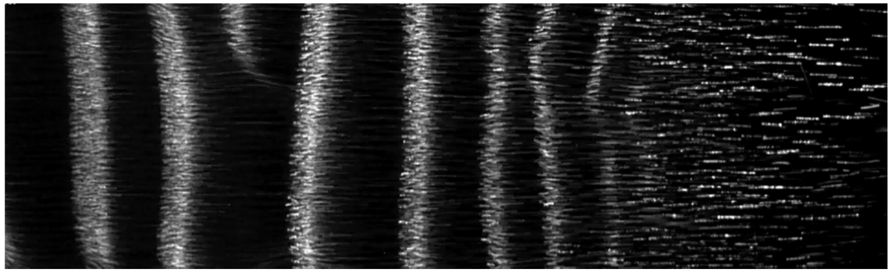
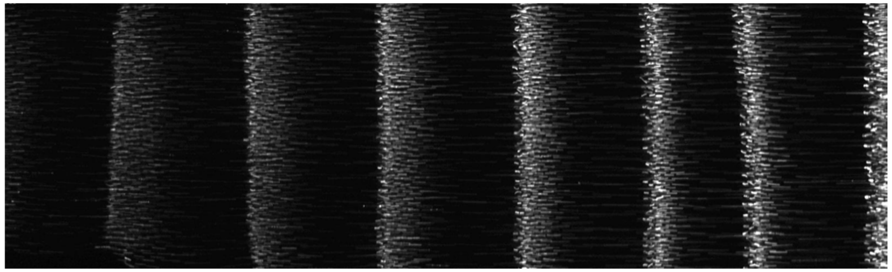
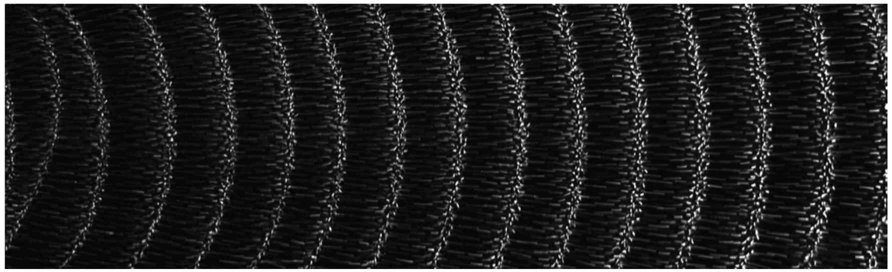
Density waves

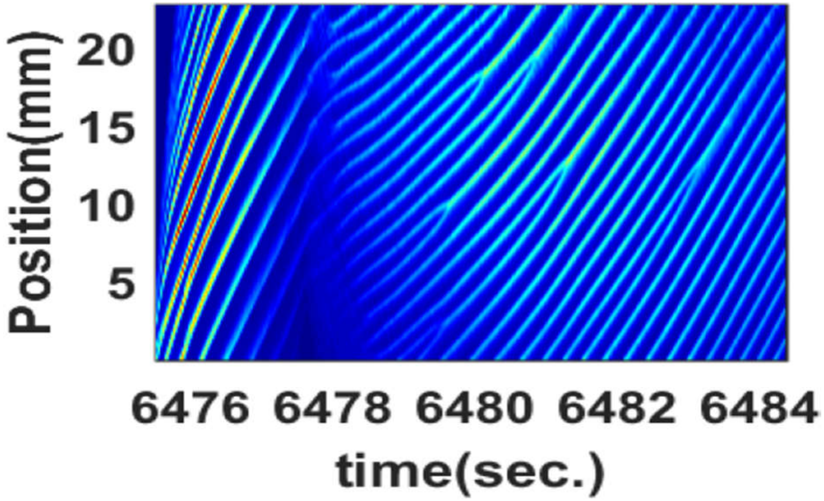


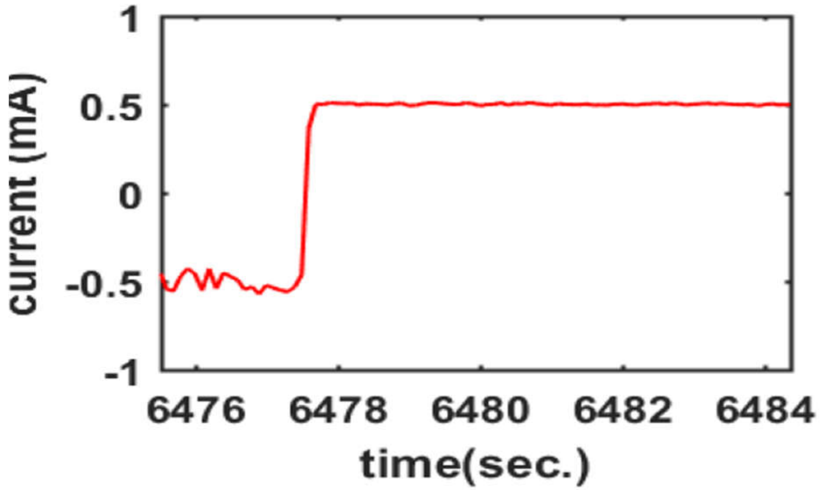
Negative polarity



Positive polarity







Jaiswal, PoP 2018

Summary

- complex/dusty plasma is an interdisciplinary research field combining all four states of matter
- complex plasma is a new state of soft matter
- where does it belong to? fundamental physics, fluid physics, material physics, soft matter physics, space physics

→ it covers all - allows a broad range of basic/fundamental studies

Conclusion - Research under µg conditions

- complements the research on ground
- allows „pure“ investigations in the bulk plasma and new insights into:
  - Plasma-particle interaction
  - Particle-particle interaction
  - Start of collective behaviour
- Opened new research topics:
  - Electrorheological plasmas
  - Phase separation in binary mixtures

→ continue research of plasma state of soft matter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THANK YOU