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Dust Crystals Interaction with Plasma Jets

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Summer College on Plasma Physics, ICTP, August 23-28, 2009

Topics

1. Dust in low ionized gases: plasma crystals in ion flows

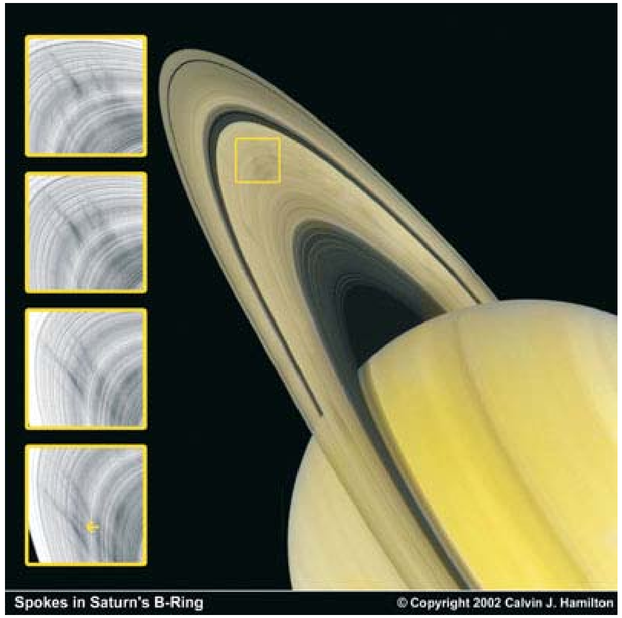
2. Dust in highly ionized plasma jets: dust acceleration to hypervelocity

3. Dust crystal in plasma jets

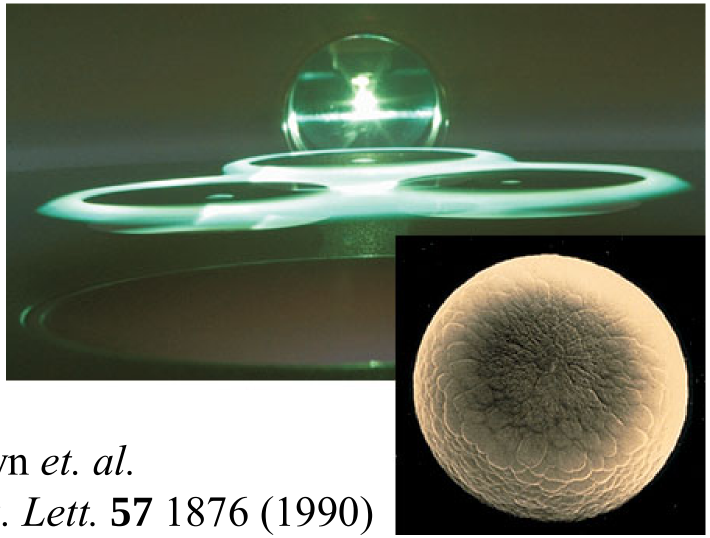
4. Conlusions

Dust is ubiquitous in nature

Dust is present in noctilucent clouds, comet tails, planetary rings, etc.



R. L. Merlino and J. A. Goree, Phys. Today 57, 32 (2004)



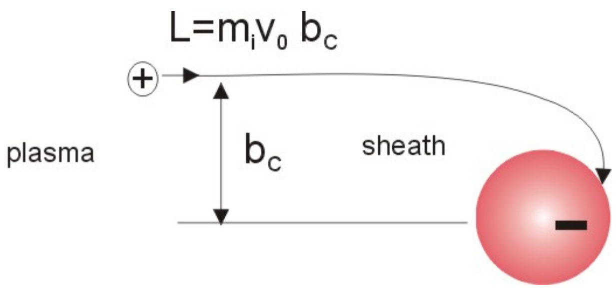
G.S. Selwyn *et. al.*
Appl. Phys. Lett. **57** 1876 (1990)

•Dust is also present in laboratory plasmas: reactors, fusion devices, dusty plasmas

Charge on a dust grain in typical lab. plasmas is ~10^3-10^5 e

Dust is considered a spherical capacitor ($r_d \ll \lambda_D$): $Q_d = C_d V_d = 4\pi\varepsilon_0 r_d V_d$

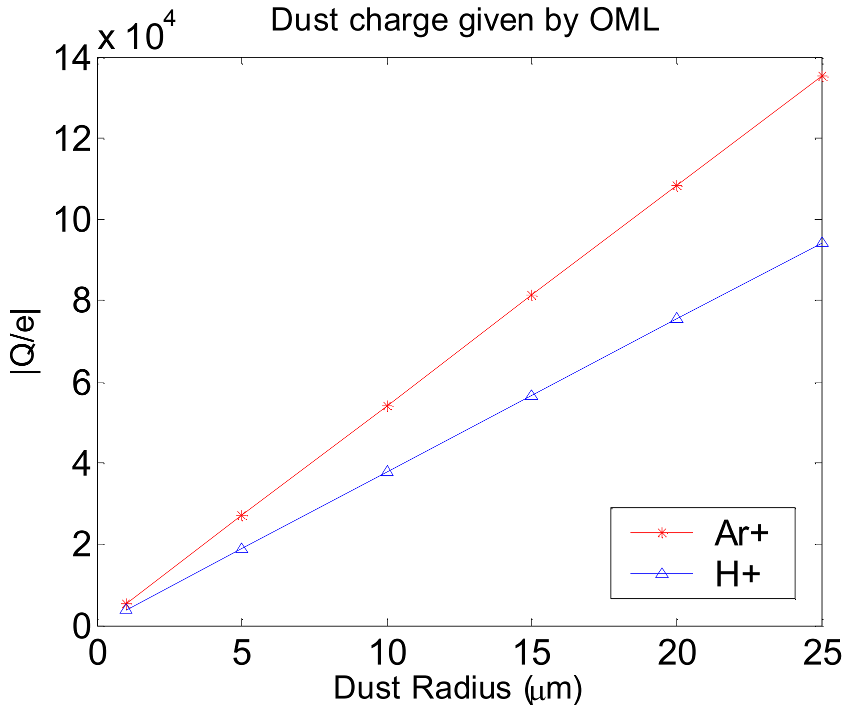
Solve numerically $I_e = I_i$ in OML (orbital motion limited)



~collection radius >r_d

$$\exp\left(\frac{eV_d}{k_B T_e}\right) = \sqrt{\frac{\pi m_e}{8 m_i}}\left(1 - \frac{2eV_d}{k_B T_e}\right) \quad (V_d < 0)$$

~I_e ~I_i



Directions in experimental dusty plasma

	Dust crystals in rf, dc plasmas, Q machines, etc	Dust in fusion (including dense plasma jets)	Dust crystals & Plasma Jets
Dust/plasma:	$r_d << \lambda_D$ (~100 μm)	$r_d \geq \lambda_D$ (~0.1-1 μm)	r_d ~1…10 μm λ_D ~10…100 μm
Some features:	•strongly coupled→crystals •ion wakes in rf sheath→ vertical alignment, oscillations & instabilities	•Dusts screened by plasma •highly accelerated dust •dust ablation	•transition from strongly to weakly coupled

Directions in experimental dusty plasma (cont.)

	Dust crystals in rf, dc plasmas, Q machines, etc	Dust in fusion (including dense plasma flows)	Dust crystals & Plasma Jets
Dominant forces:	•electrostatic •friction with neutrals •plasma drag (impact and Coulomb)*-in certain parameter ranges and small dust*	•plasma drag: -impact -*dominant* -Coulomb •electrostatic (near the edge of fusion devices)	•electrostatic •friction with neutrals •plasma drag (impact)
Dust dynamics:	•equilibrium •v_d~0-0.01 m/s, •a_d~1-10 cm/s^2	•v_d~0-5000 m/s, •a_d~10^3-10^7 m/s^2	•v_d~0-0.1 m/s, •a_d~1-10^2 m/s^2

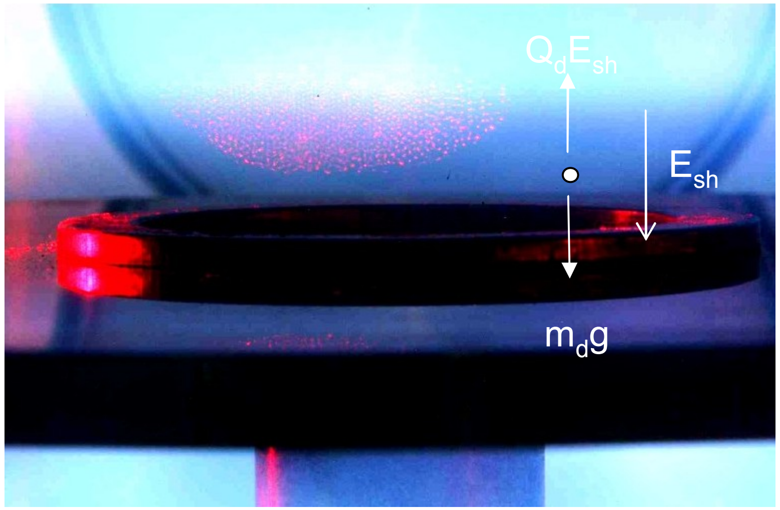
Crystals in RF plasma sheath

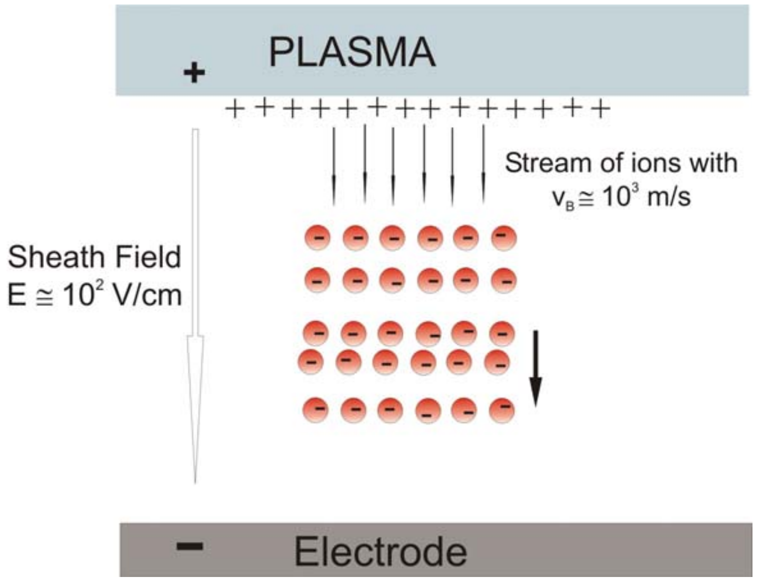
- RF frequency f=13.56 Mhz

(self-bias≈ -10…-100 V) (p-p ~50-200 V)

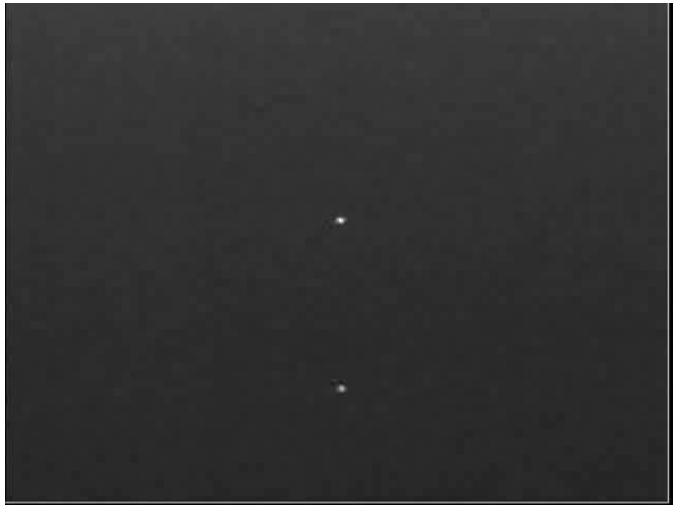
$$V_{electrode} = V_{dc} + V_{rf}\sin(2\pi f\, t)$$

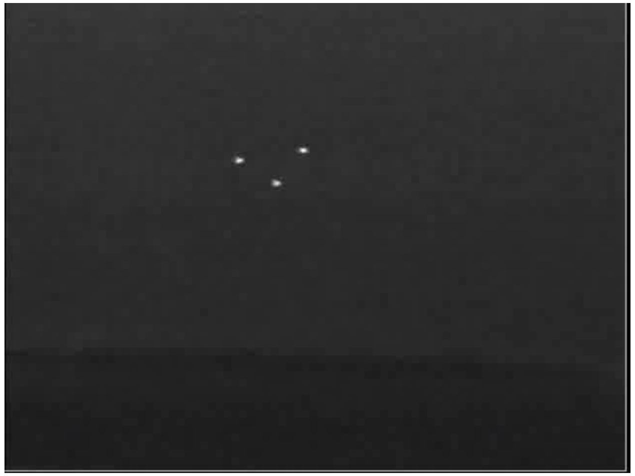
- Dust has inertia → in equilibrium $Q_d E_{sh} = m_d g$ (E_{sh} is time averaged sheath field)





Effect of ion flow on small dust clusters

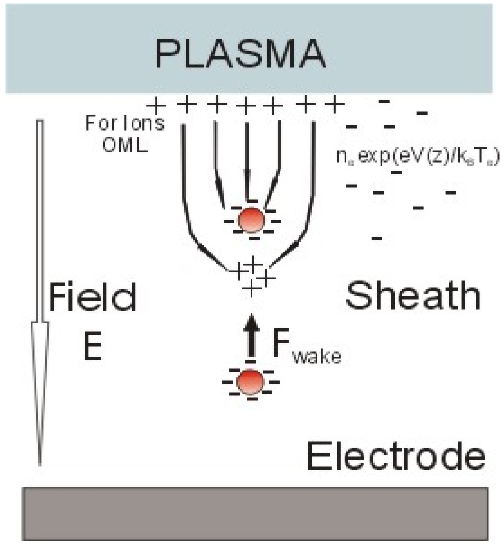




•Ion focusing in RF sheath creates attractive potential well

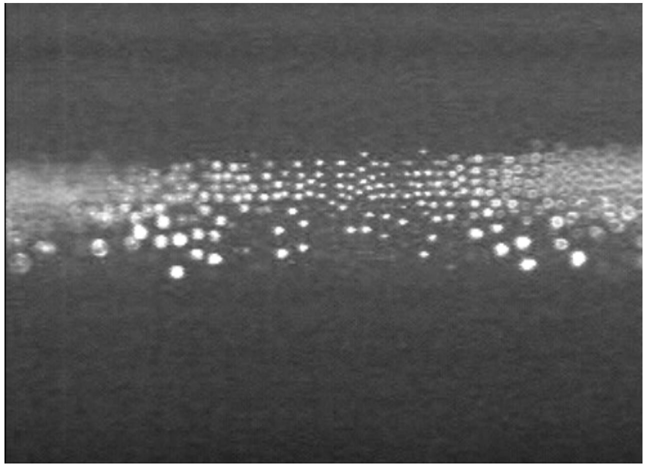
•For specific pressures and at constant RF power, spontaneous low-frequency oscillations of the lower grain are observed.

CM Ticos, P.W. Smith, PK Shukla, PLA 2003

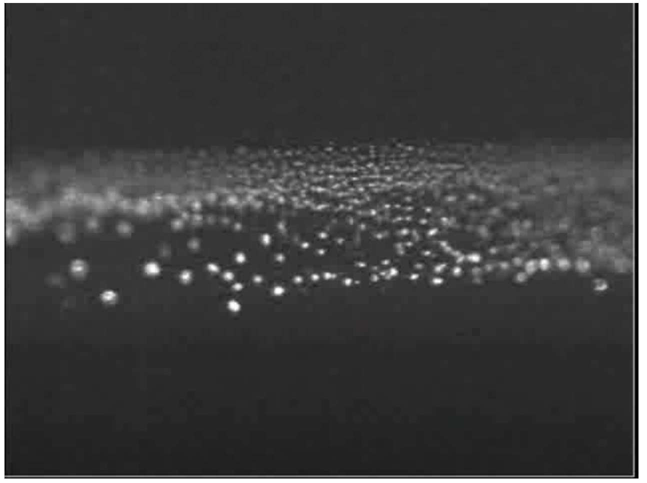


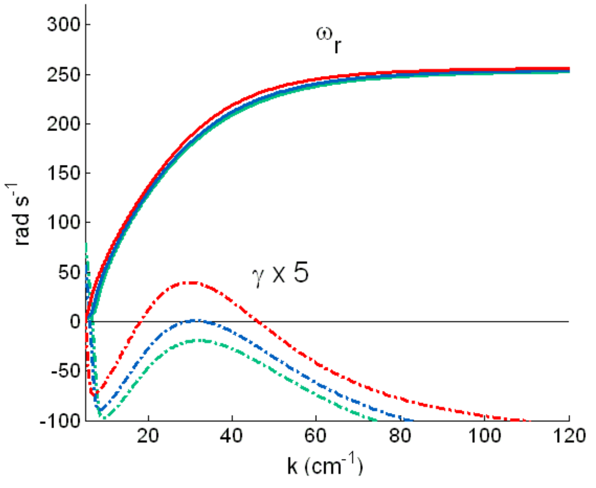
Effect of ion flow on dust crystals

Stable crystal: $P=0.198$ Torr



Propagating waves: $P=0.185$ Torr





$$1+\frac{1}{k_B^2\lambda_{De}^2}-\frac{\omega_{pd}^2}{\omega(\omega+i\nu_d)}-\frac{\omega_{pi}^2}{(ku+\omega)(ku+\omega-i\nu_i)}=0$$

$$u \parallel k,\quad u\cong u_B >> v_{Ti},\quad ku, kv_{Te} >> \omega >> kv_{Td}, T_e >> T_i$$

Solve numerically $\omega(k)$ *where* $\omega=\omega_r+i\gamma$:

$\gamma<0, \quad P=0.3$ Torr (green)

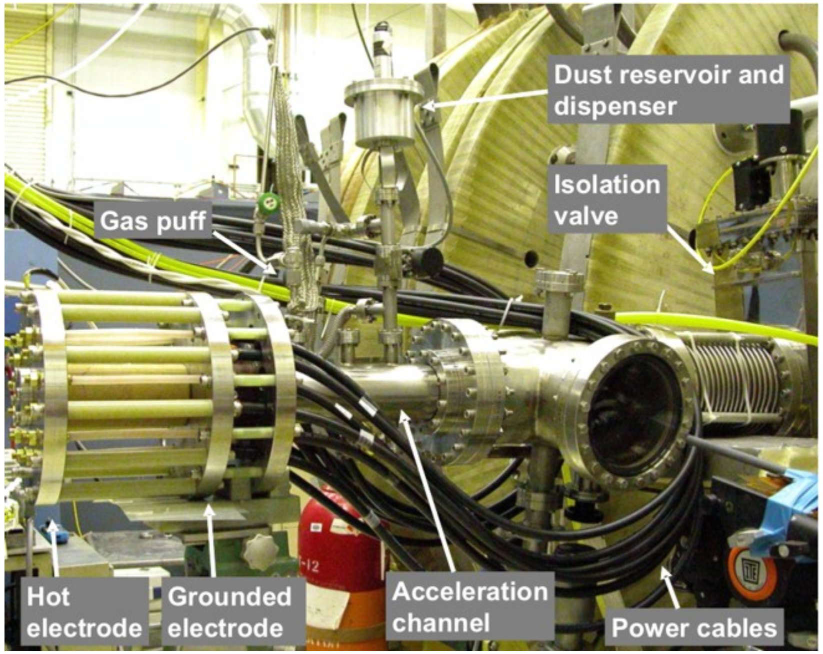
$\gamma=0, \quad P_C\approx 0.275$ Torr (blue)

$\gamma>0, \quad P=0.23$ Torr (red)

CM Ticos, A. Dyson, P.W. Smith, PK Shukla, PPCF 2004

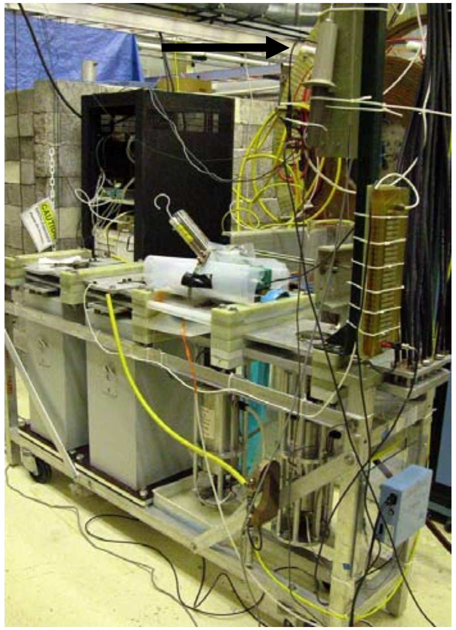
Plasmadynamic dust accelerator using dense plasma jets

Plasmadynamic dust accelerator



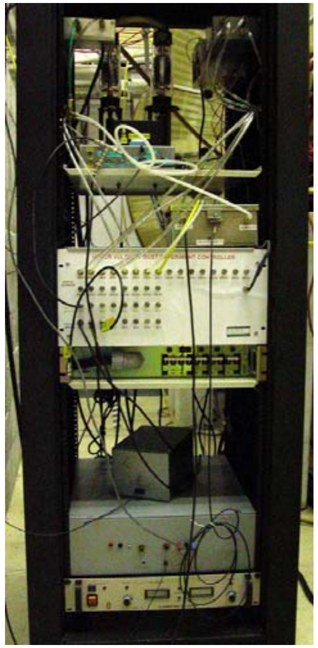
•uses deuterium puffed at ~150 psi
•coaxial S.S. electrodes

Power & diagnostic systems



• capacitor bank =1 mF
• charged up to 10 kV
• current and voltage probes
•energy ~ 50 kJ

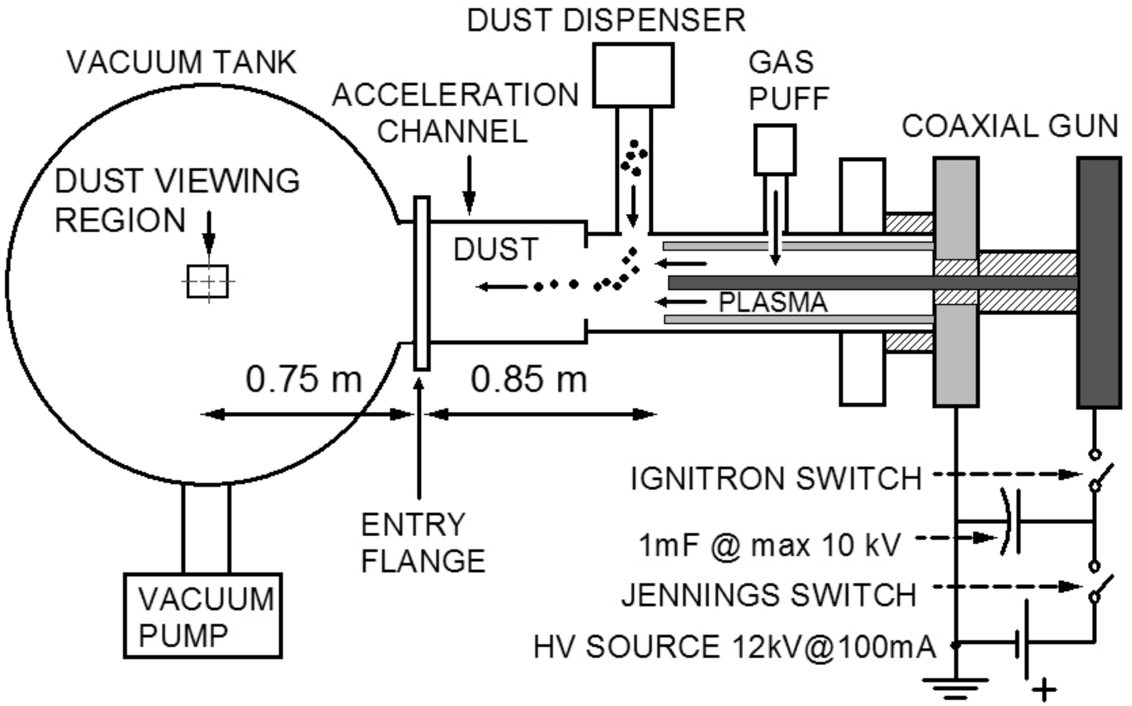
Control system



• Field Point modules running real-time LabView

CM Ticos , Z Wang, L Dorf, G Wurden, RSI 2006

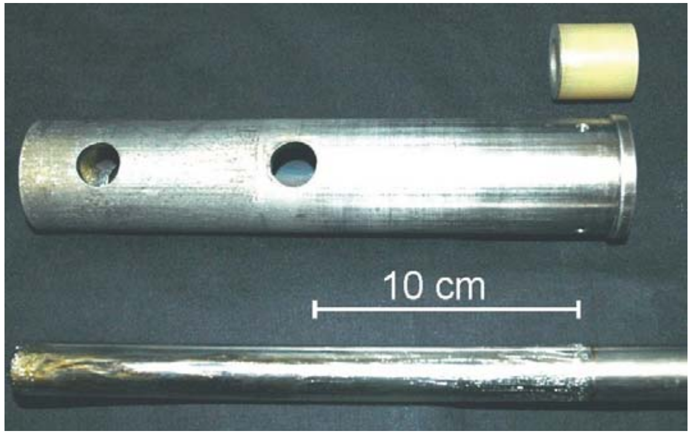
Experimental set-up

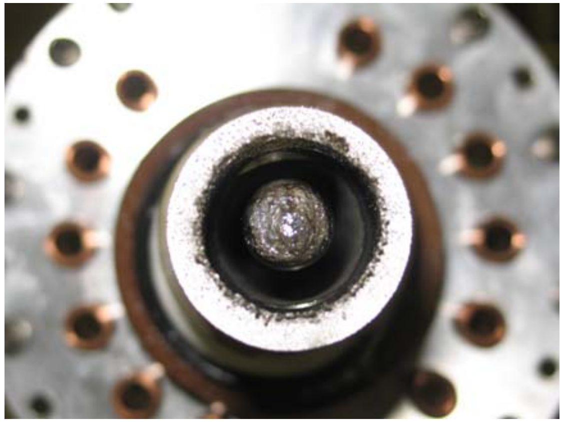


- DICAMPRO (ICCD, gating ns to μs)
- Plasma imaging: Fish eye lens 16 mm f/4 (Nikon)
- Dust detection: Telephoto lens 500 mm f/4 (Sigma)

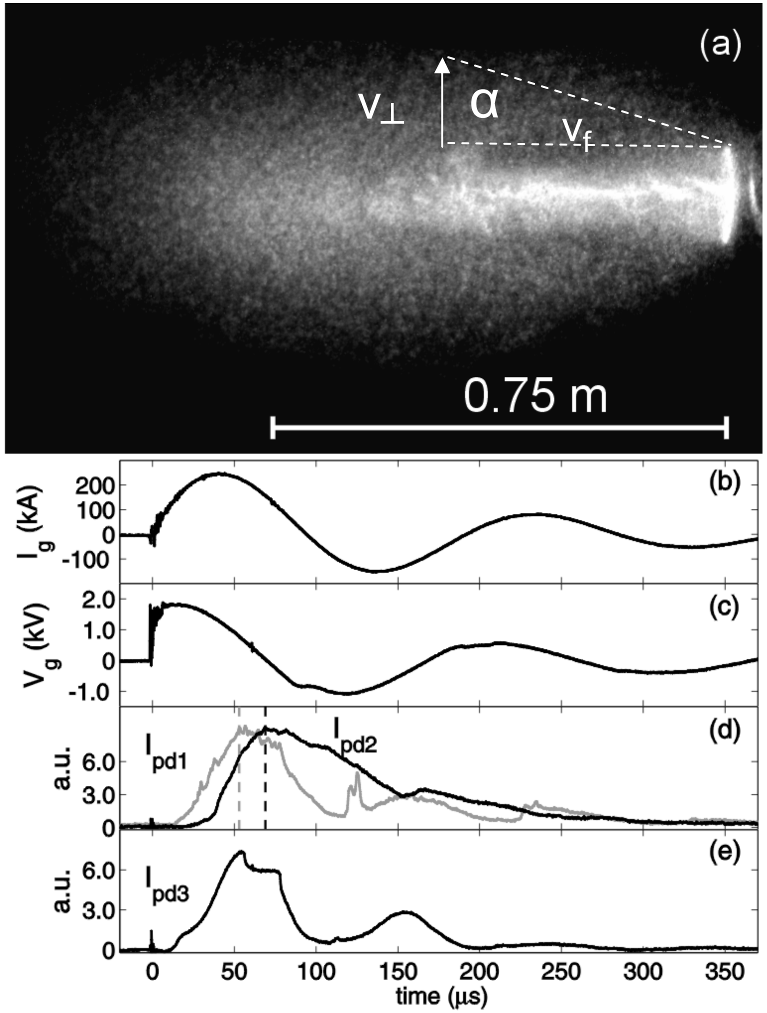
Coaxial gun for plasma flow generation

- center electrode Ø ~ 1.9 cm, coax electrode $Ø_i$ ~ 3.2 cm
- coax gap length ~ 21 cm
- 12 coax cables RG-217 (~peak 20 kA /each)
- 10-30 torr L/shot deuterium





Speed and temperature of supersonic plasma jet



•V=10 kV

•Exposure 50 ns

$I_{max} \approx$ 247 kA,

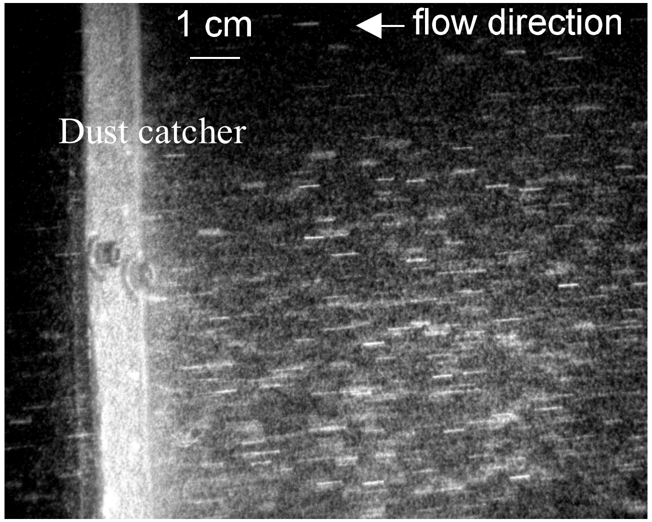
←Side-view photodiodes Δt =16μs@0.9m and $\mathbf{v_f \approx 56}$ **km/s.** $\mathbf{T_i}$**~2.8 eV** from $v_\perp$

3<M<4

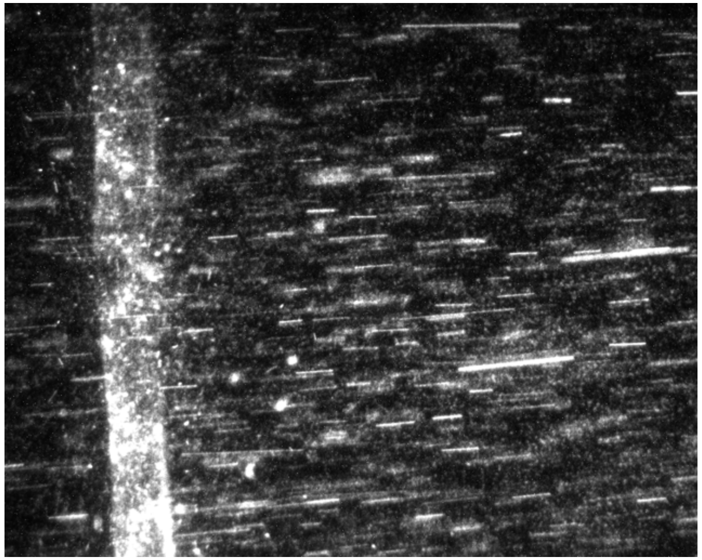
←End-on view photodiode

CM Ticos, Z Wang, G Wurden, LA Dorf, JL Kline, DS Montgomery, PK Shukla, PRL 2008

Imaging of hypervelocity graphite dust



- Graphite/diamond dust: 1 to 60μm (imaged grains >10 μm)
- Self-illuminated dusts→ trajectory looks like tracer
- Exposure 4-16μs



CM Ticos, Z. Wang, GA Wurden PoP 2008& IEEE Trans Pl Sc 2008

Plasma jet parameters

Plasma density: spectrometer & streak camera

•fiber@ 0.25 m gun muzzle

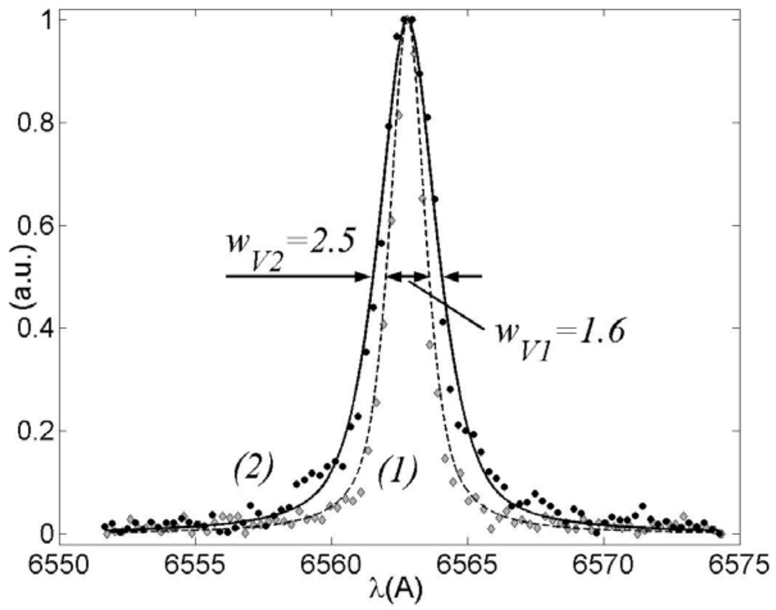
•FWHM of Dα (Stark broadening)

10 kV shot:

(1) at 75 μs

(2) at 90 μs

from t=0

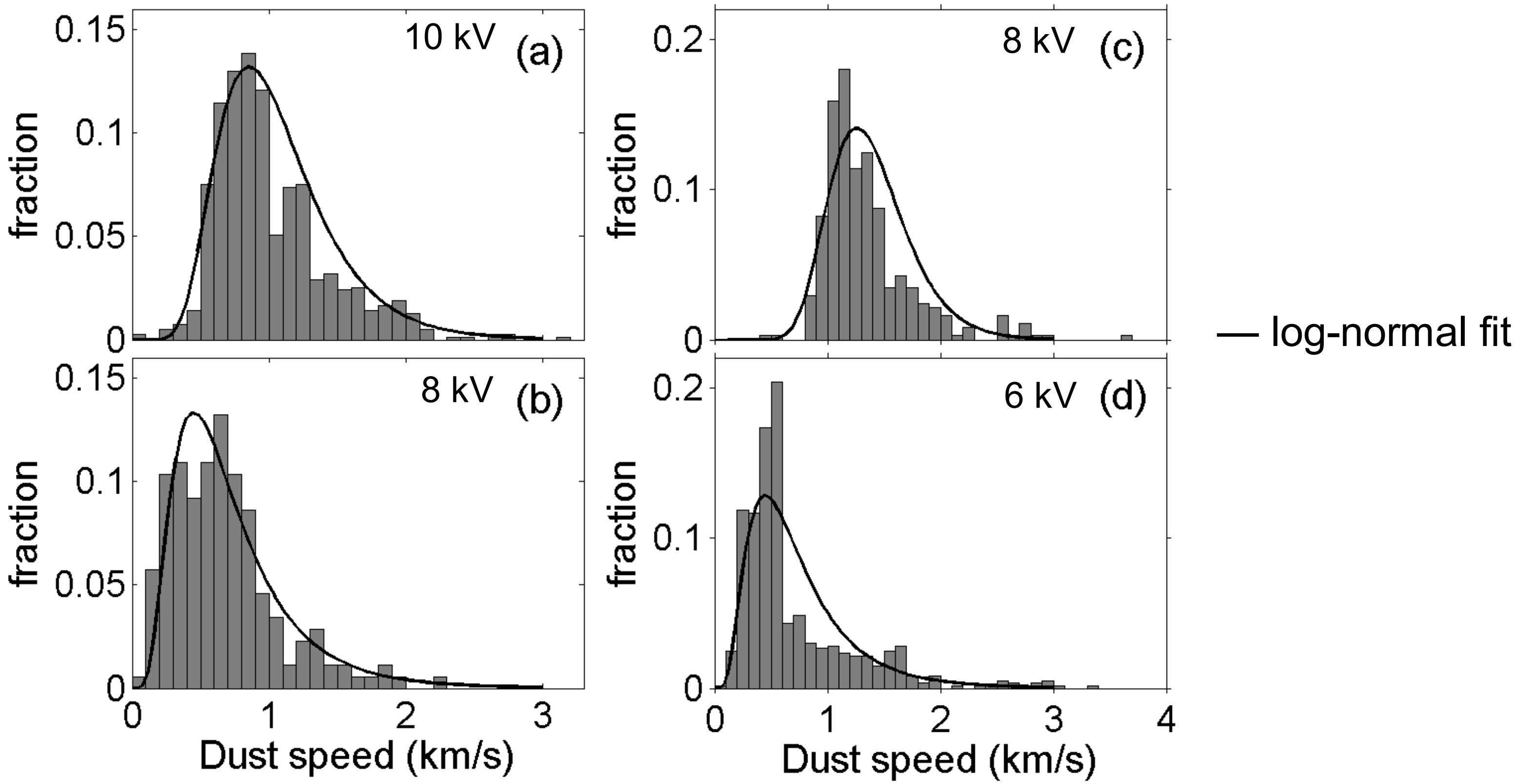


Voltage (kV)	v_f (km/s)	$n_i(\times 10^{22}\ m^{-3})$	T_i (eV)
6	26 ± 0.5	0.2–1.5 ± 0.1	1.3 ± 0.3
8	38 ± 1	0.5–2.2 ± 0.1	1.7 ± 0.4
10	56 ± 2	0.5–3.1 ± 0.2	2.8 ± 0.7

Dust speed distribution

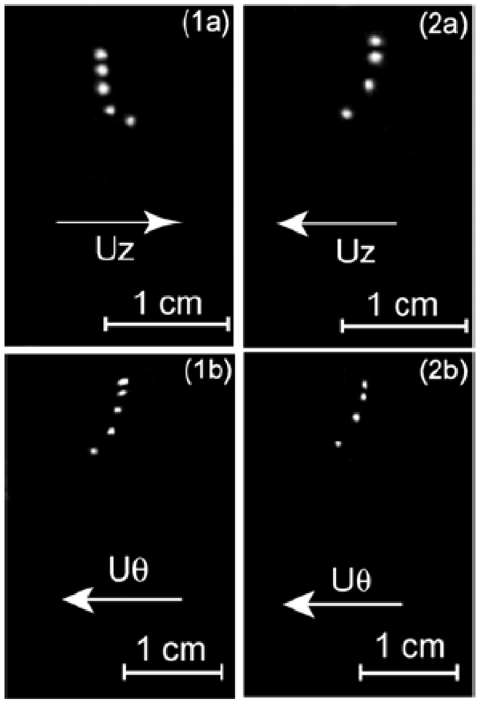
(a)&(b) Diamond dust
diameter 40 to 60 μm
ρd= 3.52 g/cm3

(c)&(d) Graphite dust
diameter 1 to 44 μm
ρd= 2.25 g/cm3



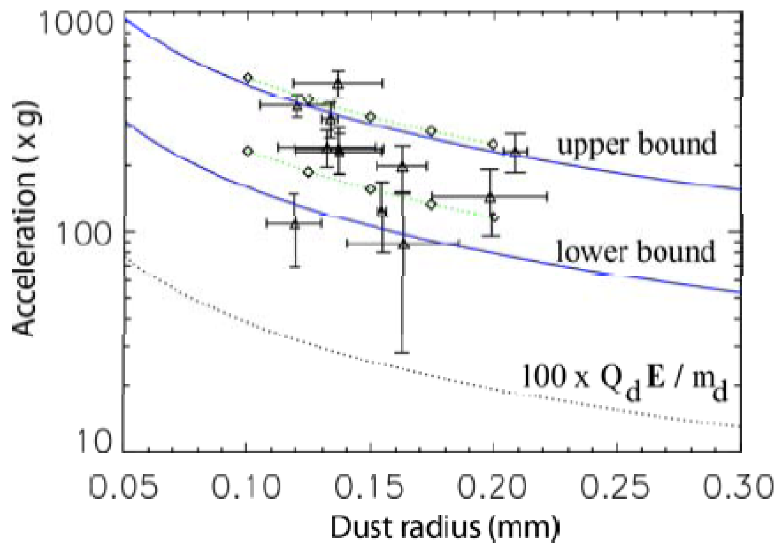
Dust dynamics in highly ionized plasma flows dominated by ion drag

- Dust dynamics is dominated by plasma (ion)-drag in the Flowing Magnetized Plasma (FMP) Experiment at Los Alamos
- $n_e = n_i \sim 10^{19}$ m^{-3}, T_i, $T_e \sim 10$ eV, $\mathbf{U} \sim 10$-15 km/s (plasma flow speed)



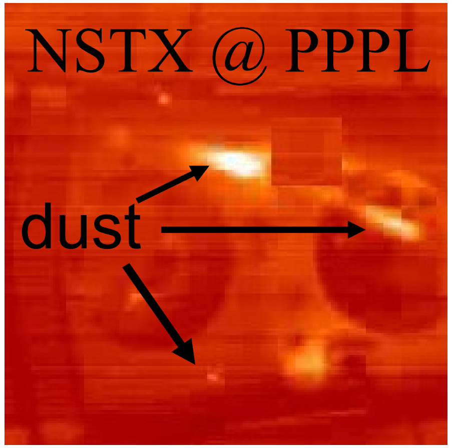
Ion-drag (direct impact): $\mathbf{F}_{pf} = 2\pi r_d^2 k_B T_i n_i \xi \mathbf{w}$

$$\mathbf{w} \equiv \mathbf{U}/\sqrt{2k_B T_i/m_i} \qquad \xi = 1.1 \sim 1.5$$

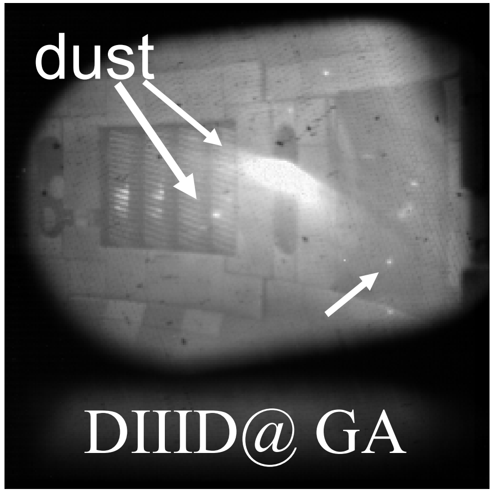


Z. Wang, C.M. Ticos, G. Wurden, PoP 2007

Moving dust in fusion devices



http://nstx.pppl.gov/index.html



D.L. Rudakov et al., "Dust in Fusion Plasmas"-
DFP/EPS 2007 34th EPS, July 8-10, 2007, Poland

Dust is mostly peeled from the walls:

- ne, ni ~10^{19} m-3 (edge)….10^{21} m^{-3} (core),
- Te, Ti ~10 eV (edge) …10^3 eV (core)
- Dust size ~0.1-100 μm
- Dust speed in NSTX and DIIID: ~10-200 m/s

- It appears that dust motion is determined by plasma flow

Dust crystal & plasma jet experiment

Experiment for studying the interaction between a dust crystal and an incident plasma jet (funded by the National University Research Council, Romania)

- Dust crystal in sheath of rf plasma (ne $\approx 10^{15}$m-3) with ions ($\approx$ 0.025 eV) and Te~1eV
- Plasma jet: higher density (ne >10^{16} m^3) and flowing at ~km/s.

- RF plasma used to levitate the crystal
- Plasma jet produced in a minicoaxial gun (inner Φ=15 mm)

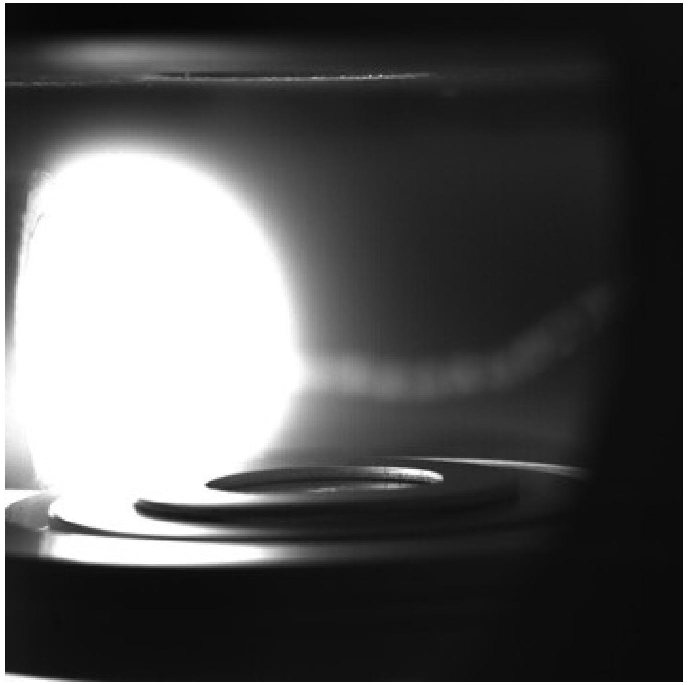
Goals of Dust Crystal & Plasma Jet Experiment

- Monitor at microscopic level the interaction of plasma jet with dust particles and dust crystals
- Track the changes induced by the plasma flow in the dust-dust interactions and in the structure of the crystal;
- To study the interaction of a plasma-dragged dust cloud colliding with a plasma crystal
- To identify and measure dust instabilities and dust waves induced by the plasma flow within the crystal
- To measure accurately the drag force of the plasma wind

Jet from minicoaxial plasma gun

- Capacitor bank of 12 μF
- Charged up to 1000 V (low energy~10 J)
- Diagnostics:, current and voltage probes,

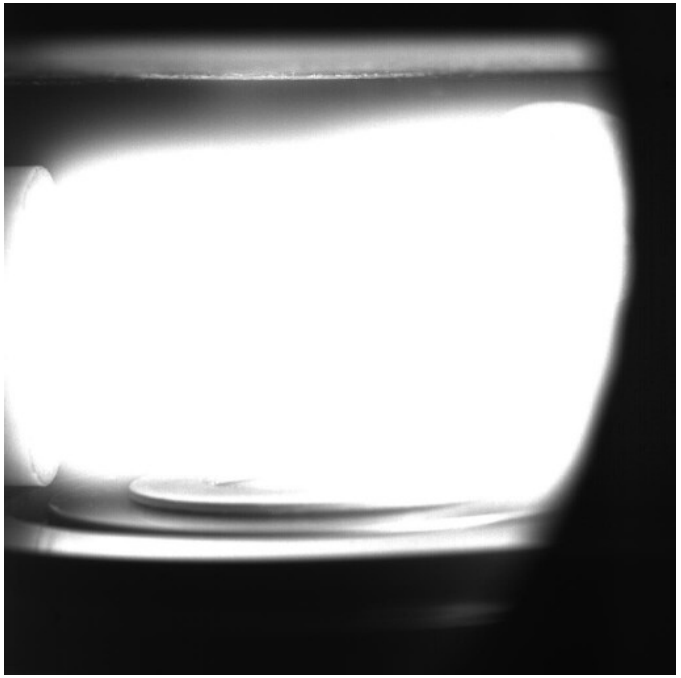
fast imaging (Photron 1024-PCI Camera up to 105 000 fps, but at only 128x16 pixels)



- 125 fps;
- shutter 8ms

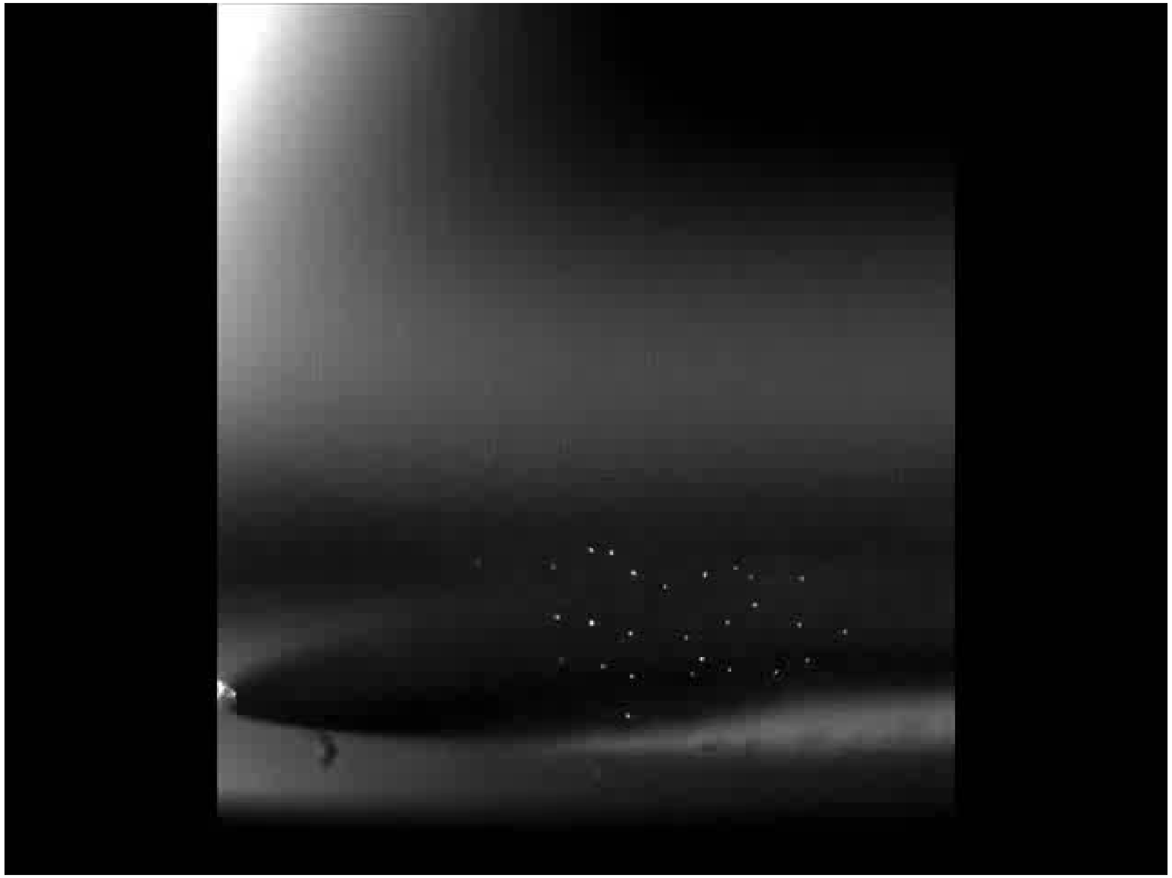
- lower limit of

jet speed: 1 km/s



Dust crystal interaction with plasma jet: preliminary results

Plasma jet approaching from left



Plasma crystal

Dust crystal interaction with plasma flow: preliminary results

Experimental Observations:

- Dust is flying upward due to ion drag (direction of plasma flow) at a speed ~1-10 cm/s

- When plasma jet dissipates dust falls back into the sheath → parabolic trajectory

More work will be done in order to analyze the trajectories of dust particles and to diagnose the plasma

Conclusions

•Plasma crystals:

-study interaction forces in crystalline structures at convenient spatial and temporal scales (of the order of mm and only ms)→interesting physics

-dynamics deduced by fast imaging of dust trajectories

•Dust in dense plasma flows:

-accelerated to hypervelocities, heated to high temperatures

-ion drag is dominant by far

•Plasma crystals in plasma jets:

-novel experiment useful for testing theories of dust-flow and dust-dust interactions, electrostatic coupling between dusts, plasma flow drag

Thank You!