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Observation of Hypervelocity Dust in Dense Supersonic Plasma Flows: Physics and Applications.

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OBSERVATION OF HYPERVELOCITY DUST IN DENSE SUPERSONIC PLASMA FLOWS: PHYSICS AND APPLICATIONS

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Outline

1. Dust in plasma: a brief classification

2. Motivation for producing and studying hypervelocity dust

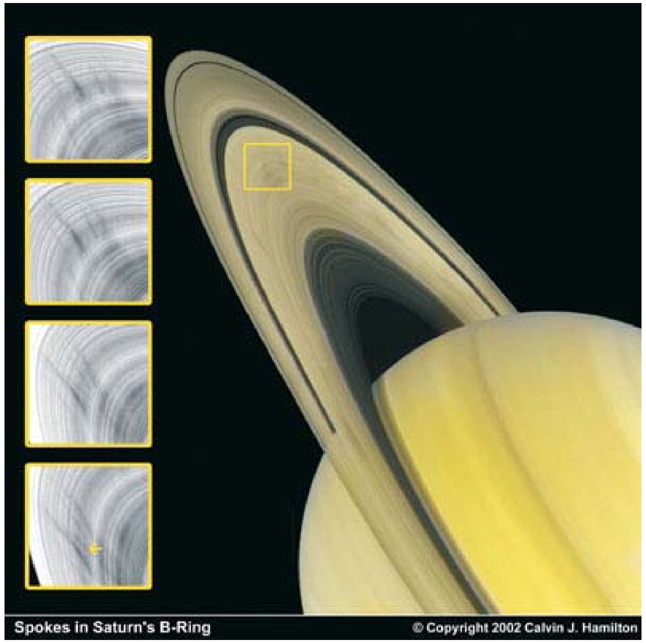
3. Experimental demonstration of dust acceleration to hypervelocities by highly ionized plasma flows

4. Physics of dust interaction with dense plasma flows

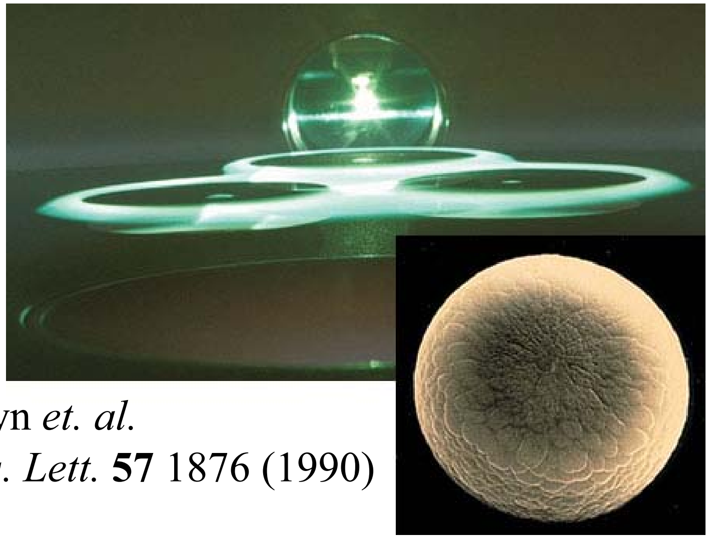
5. Applications of hypervelocity dust

Dust is ubiquitous in nature

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



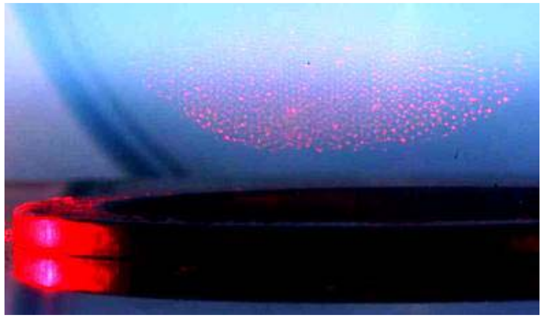
R. L. Merlino and J. A. Goree, Phys. Today 57, 32 (2004)



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

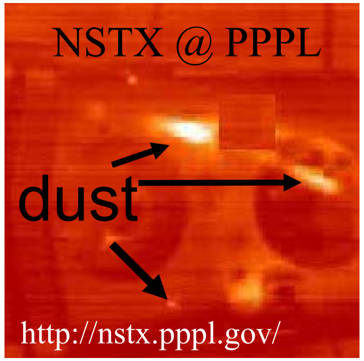
•Dust is present in laboratory plasmas: reactors, fusion devices, dusty plasmas

Comparison of dusty plasmas regimes



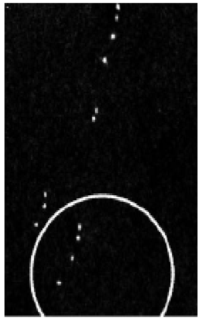
In low ionized gases (rf & dc plasmas, Q machines, etc)

- n_p~10^{13}-10^{16} m^{-3}, T_e~0.5-5 eV, T_i~0.025-0.5 eV
- Dust material: plastic, carbonaceous, metallic
- Dust size ~0.1-30 μm



In fusion plasmas:

- n_p ~10^{19}-10^{20} m^{-3}, T_e, T_i ~10 (edge)-10^3 eV (core)
- Dust material: carbonaceous, metallic
- Dust size ~0.1-100 μm



Z. Wang, CM Ticos, GA Wurden, PoP 2007

In dense plasma flows produced at Los Alamos:

- n_p ~10^{19}-10^{22} m^{-3}, T_e, T_i ~1-15 eV
- Dust material: carbonaceous, fluorescent powder
- Dust size ~1-100 μm

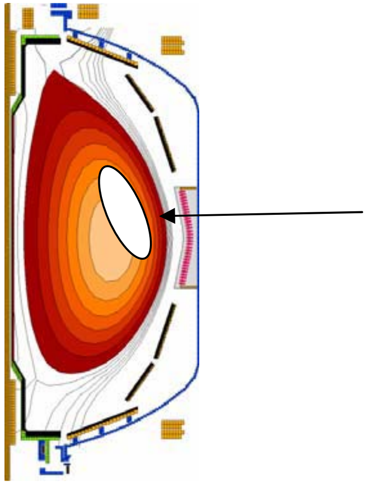
Dust dynamics in different plasma regimes

	Dust in rf, dc plasmas, Q machines, etc	Dust in the edge of fusion plasma	Dust in dense plasma flows
Dust/plasma :	$r_d << \lambda_D$ (≥100 μm)	$r_d \geq \lambda_D$ (~1-10 μm)	$r_d >> \lambda_D$ (~0.1 μm)
Dominant forces:	•electrostatic •friction with neutrals •plasma drag (impact and Coulomb)-*in certain parameter ranges*	•plasma drag (impact and Coulomb) •electrostatic	•plasma drag (impact)
Dust dynamics:	•equilibrium •v_d~0-1 cm/s, •a_d~1-10 cm/s^2	•equilibrium •v_d~0-200 m/s, •a_d~10^{3}-10^5 m/s^2	•v_d~0.1-5 km/s •a_d~10^5-10^7 m/s^2

Motivation for producing hypervelocity dust at LANL: B field mapping in NSTX plasma

- Hypervelocity dust injection (HDI) **is a new proposed diagnostic** method for magnetically confined plasmas (*Wang & Wurden, RSI 2003, 2004*)

- Intended for magnetic field mapping of the NSTX plasma

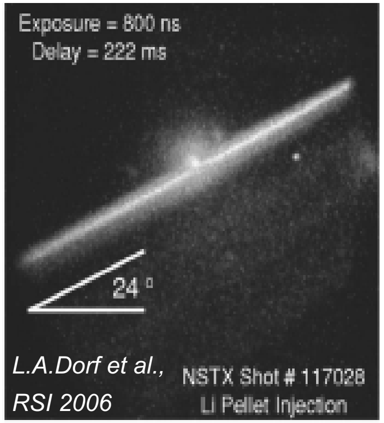


http://wsx.lanl.gov/gwurden.htm

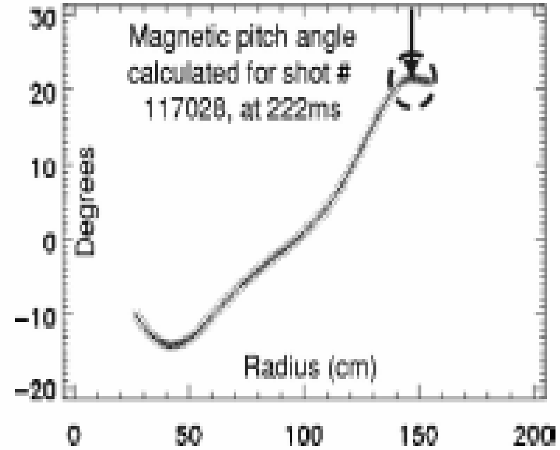
BASIC IDEA:

- Dust is launched at km/s inside plasma
- Dust material is ablated at the grain surface by plasma particle fluxes
- Dust atoms are ionized and follow the local magnetic field lines

- **Dust plume aligned with local B field!** (like in the pictures!)



Li pellet ablated in NSTX (v~150 m/s, penetration ~20 cm)



Numerical calculated pitch angle -in agreement with experiment

Techniques for measuring B field in fusion plasmas

Established methods:

- The motional Stark effect (MSE) in neutral atoms:

  - requires the injection of hydrogen beam at high speed

  - the light emitted by these atoms, excited trough collisions, is split by the E field (**E=v×B,** Stark effect)

  - difficult al low magnetic fields (~0.1 T in NSTX)

- The Zeeman splitting in the light emitted by lithium neutral atoms or pellets

- The Faraday rotation of the polarization plane of an incident laser beam

Features of Hypervelocity Dust Injection (HDI) technique

HDI Feasible diagnostic technique for fusion plasma:

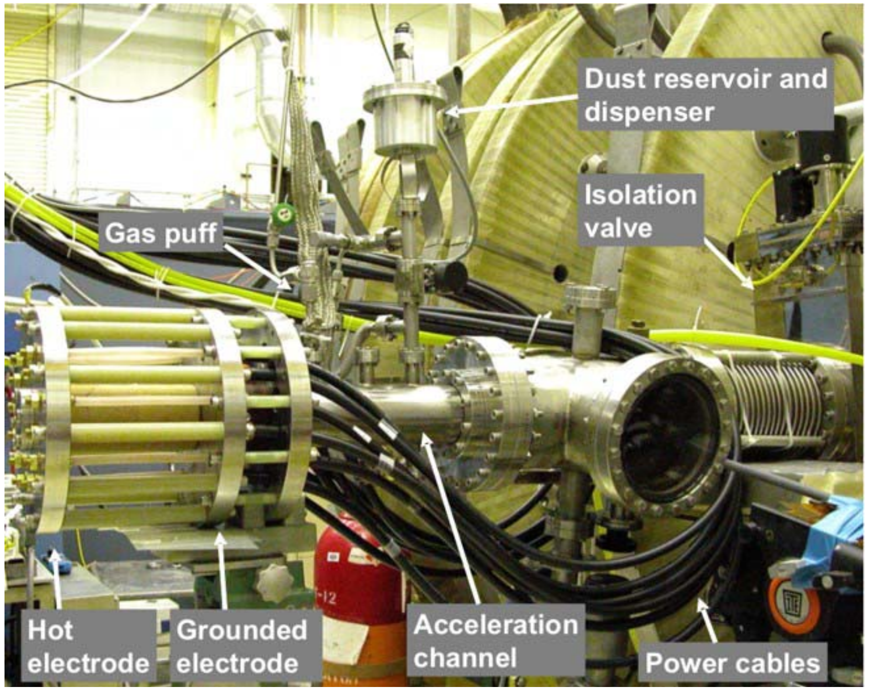
- inject many dust grains to map a larger region
- dust made of low Z material -Carbon or Lithium deutheride
- small dust particles ≤50 μm diameter to limit impurities
- uses plasma flow to accelerate dust particles

Issues:

- need to prevent plasma flow from entering the fusion plasma
- tune dust speed - hypervelocity dust must not damage the reactor tiles
- clean operation, without metal sputtering
- able to fire in a few minutes (period between shots in NSTX~15 mins)
- remote control for operation

Plasmadynamic dust accelerator built at LANL

Uses deuterium puffed at ~150 psi between 2 coaxial S.S. electrodes

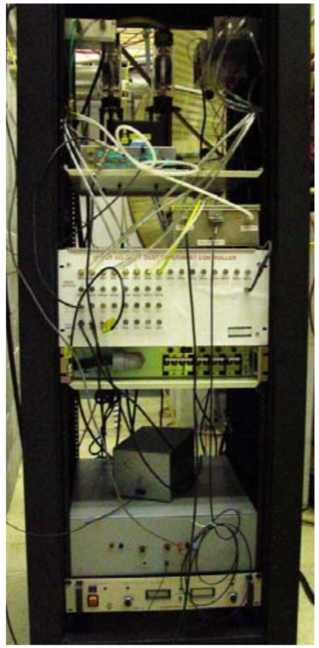


Power system

- capacitor bank 1 mF
- charged up to 10 kV
- current, voltage probes

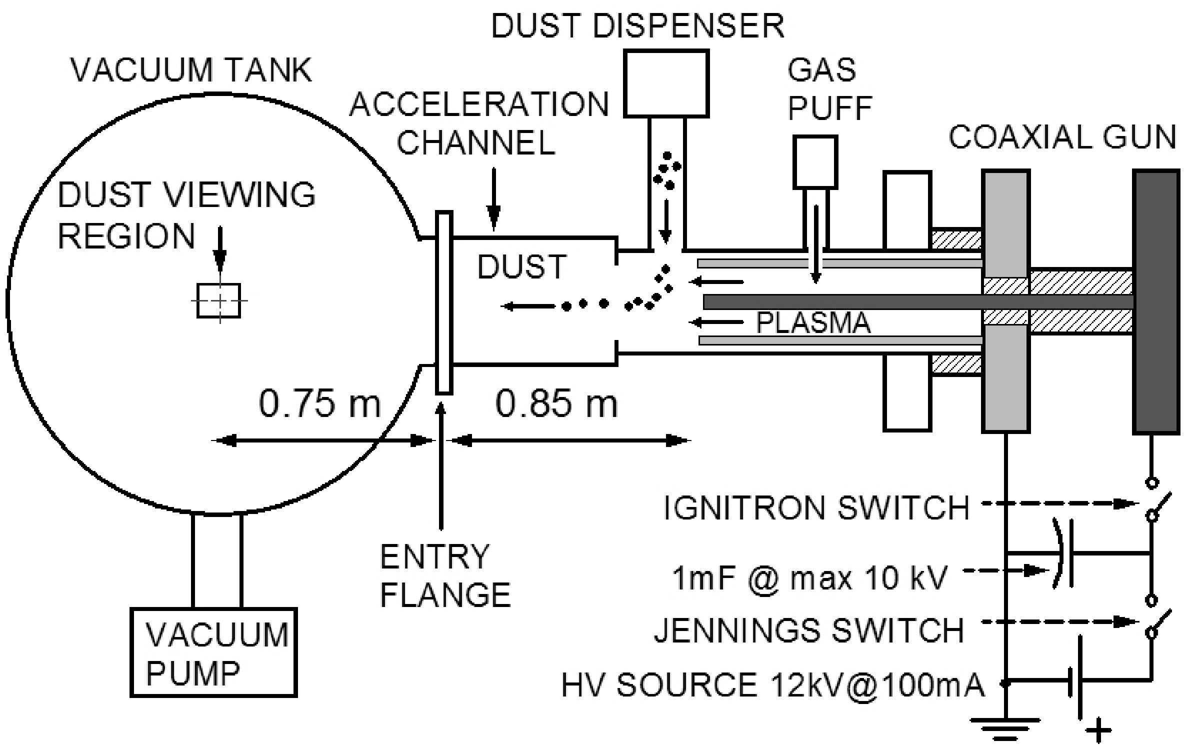
Control system

•Field Point modules running real-time LabView

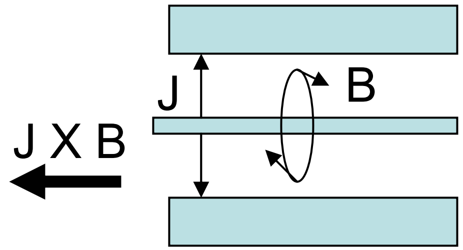


CM Ticos , Z Wang, L Dorf, G Wurden, RSI 2006

Experimental set-up for tests at Los Alamos



Plasma expelled by JxB force

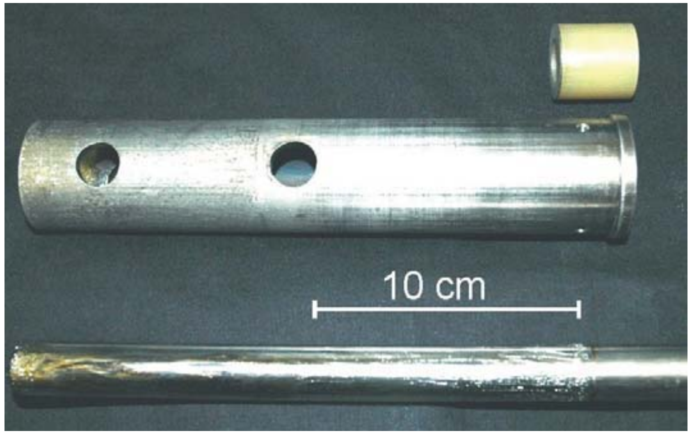


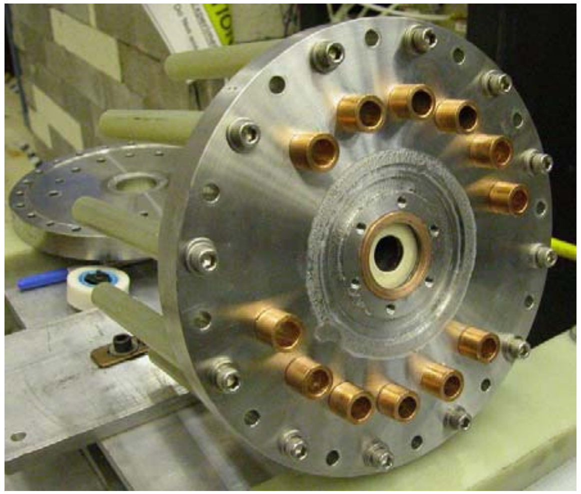
- DICAMPRO (ICCD, gating ns to μs)
- Plasma imaging: Fish eye lens 16 mm f/4 (Nikon)
- Dust detection: Telephoto lens 500 mm f/4 (Sigma)

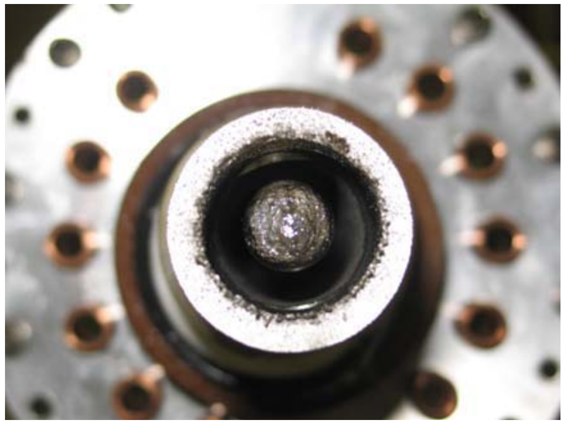
Coaxial gun for plasma flow generation

- 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

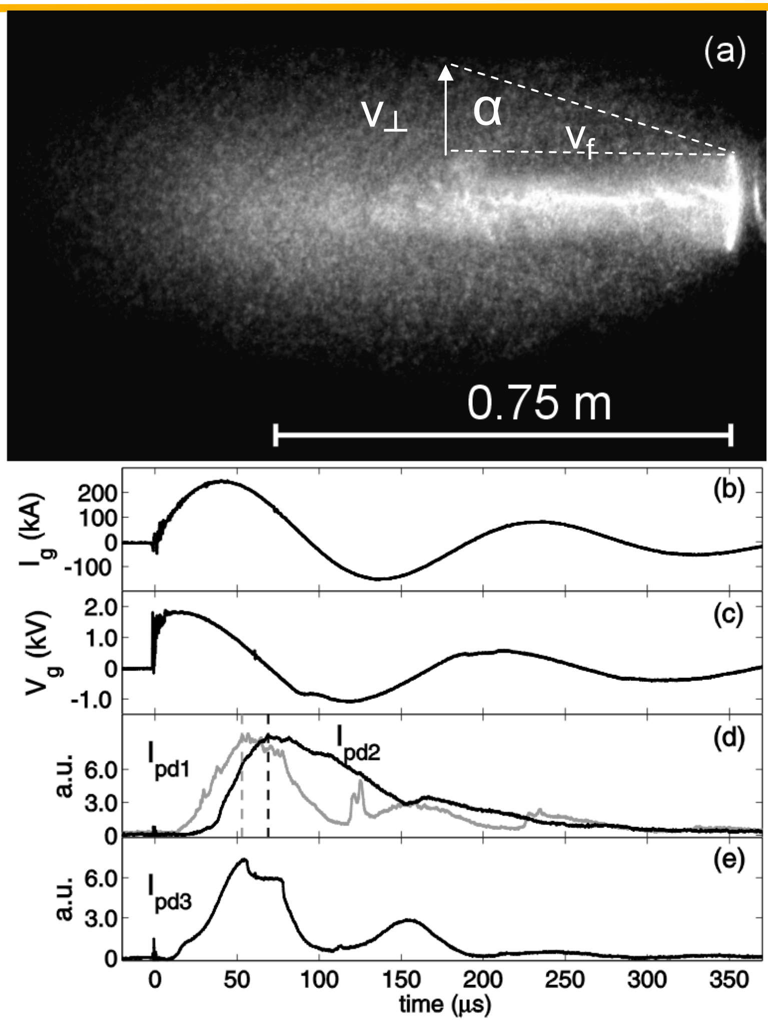
A. Hüdephol, M. Rott, E. Igenbergs, IEEE Trans. Magnetics 1989







Speed and temperature of supersonic plasma jet



•V=10 kV

•Exposure 50 ns

I_{max} ≈ 247 kA,

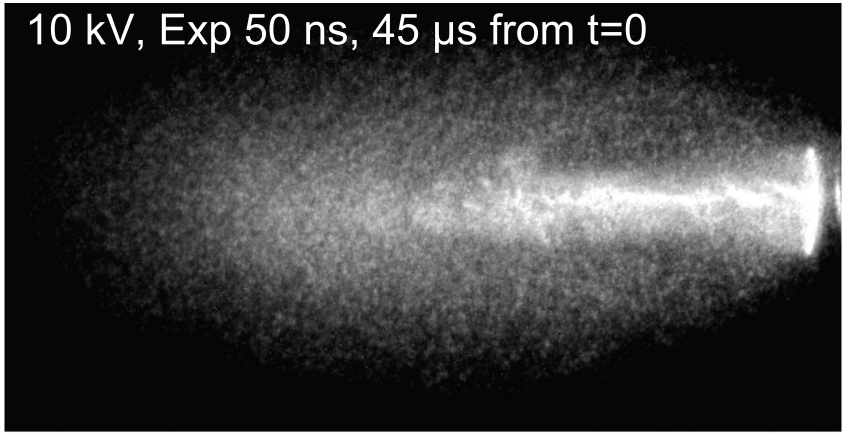
M~4

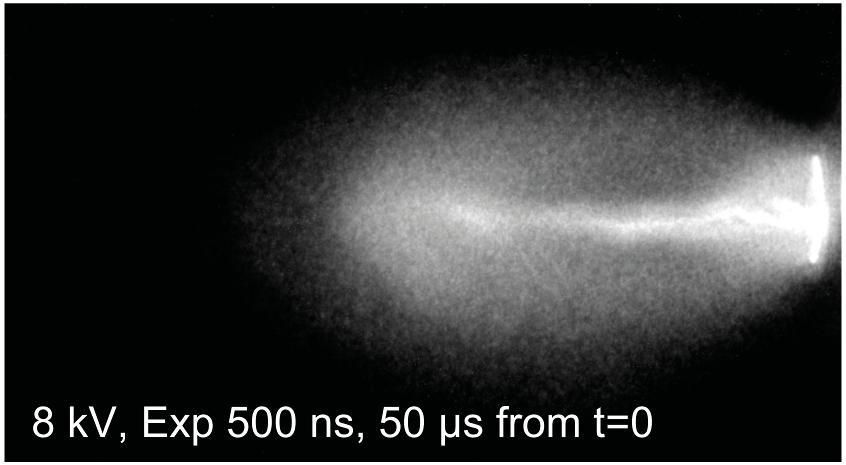
←Side-view photodiodes Δt =16μs@0.9m and **v_f ≈ 56 km/s. T_i~2.8 eV** from $v_\perp$

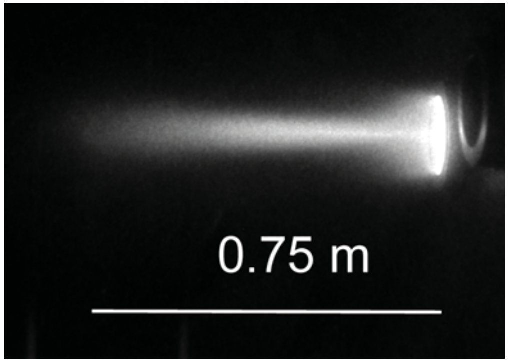
←End-on view photodiode

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

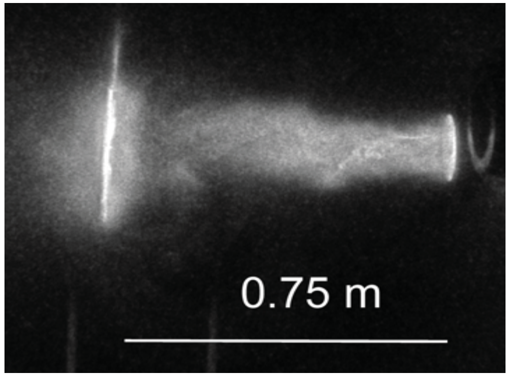
Plasma ejected from coaxial gun



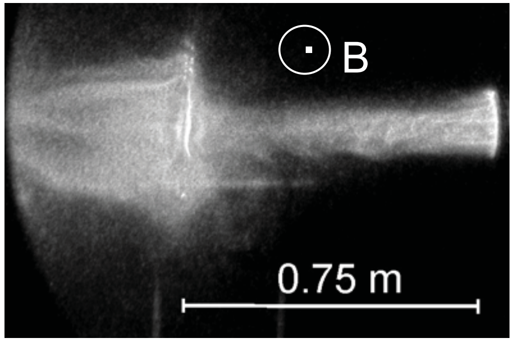




5 kV,
Exp 30 μs
40 μs from t=0



5 kV,
Exp 0.5 μs
~50 μs from t=0



5 kV,
Exp 0.5 μs
~50 μs from t=0
B=200 G

Plasma flow parameters

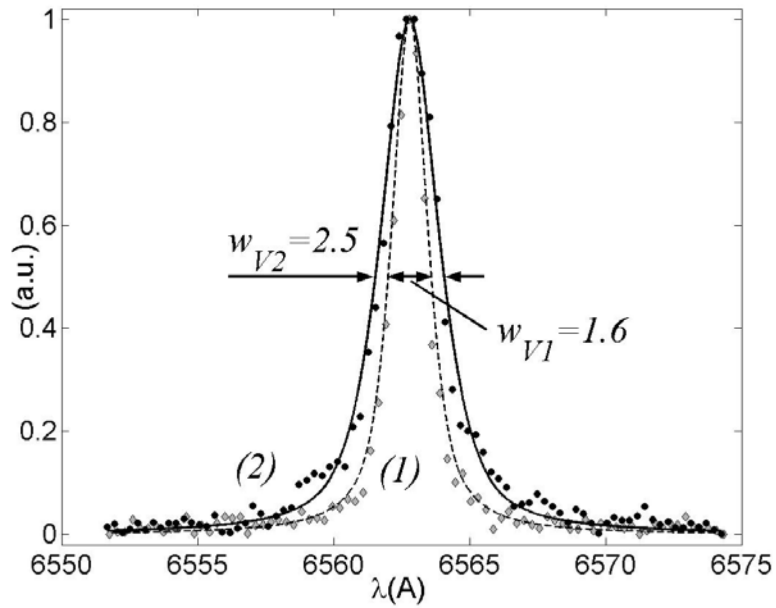
Plasma density: spectrometer & streak camera
- fiber@ 0.25 m gun muzzle
- FWHM of Dα (Stark broadening)

10 kV shot:

(1) at 75 μs

(2) at 90 μs

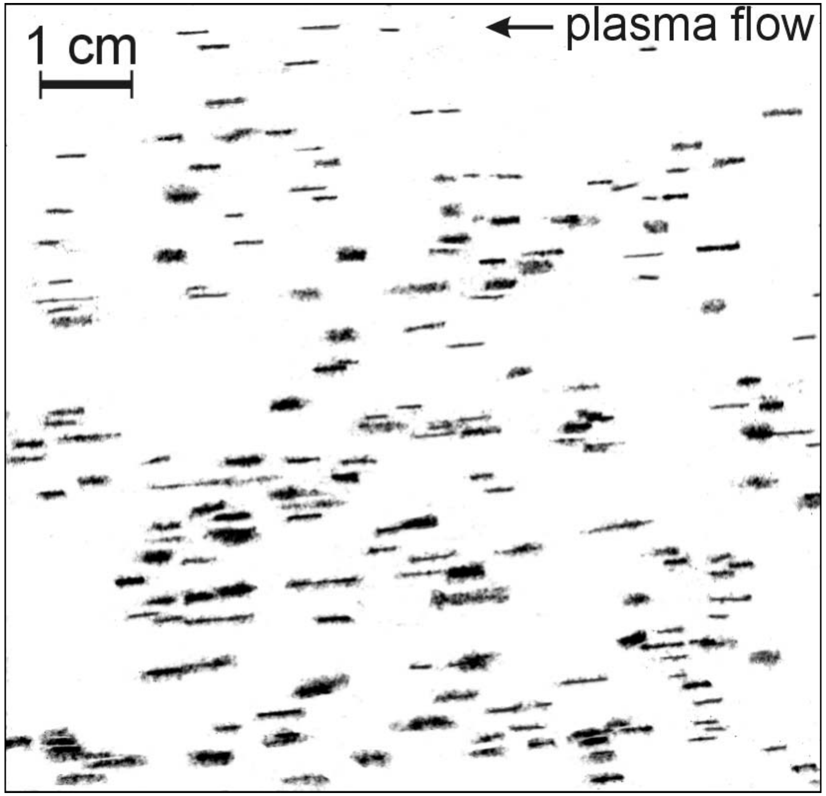
from t=0



Voltage (kV)	v_f (km/s)	$n_i(\times 10^{22}\ \mathrm{m}^{-3})$	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

Speed of self-glowing hypervelocity dust grains

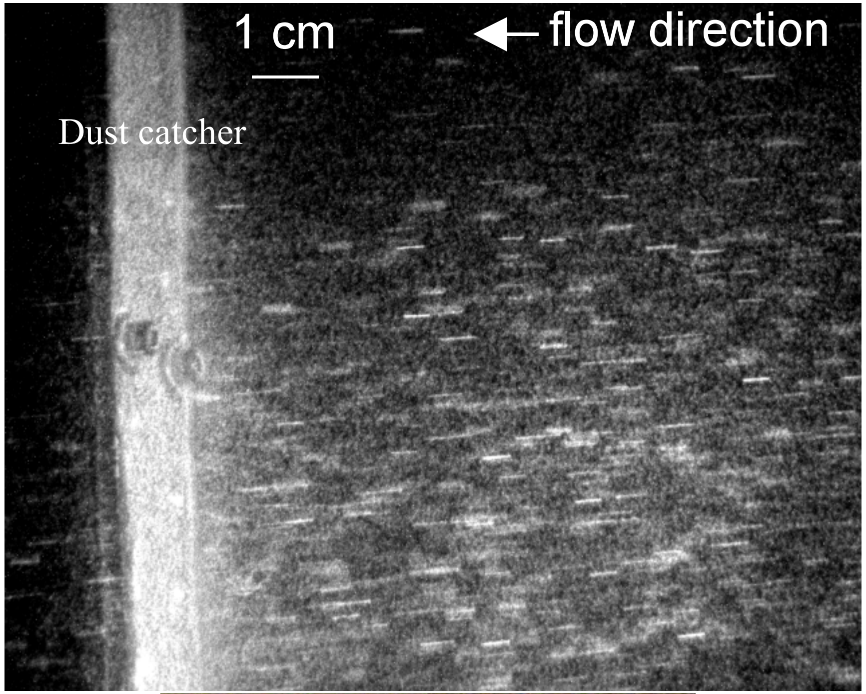
Traces of flying dust grains (inverted colors), 10kV shot

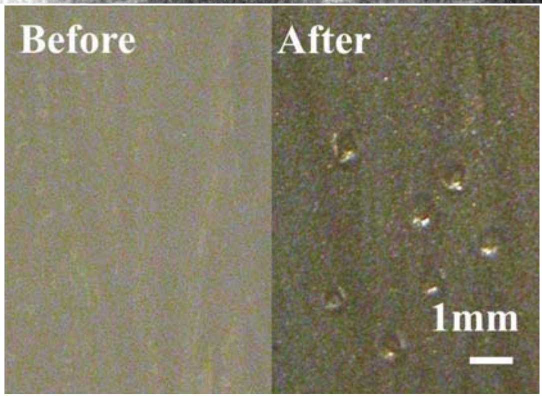


- •Dust heated by plasma→ self-illuminated
- •Diamond dust size 40 to 60 μm
- •ρd= 3.52 g/cm3
- •Exposure 4 μs

→ v_d up to **2.3 km/s (from time-of-flight)**

Imaging of hypervelocity graphite dust

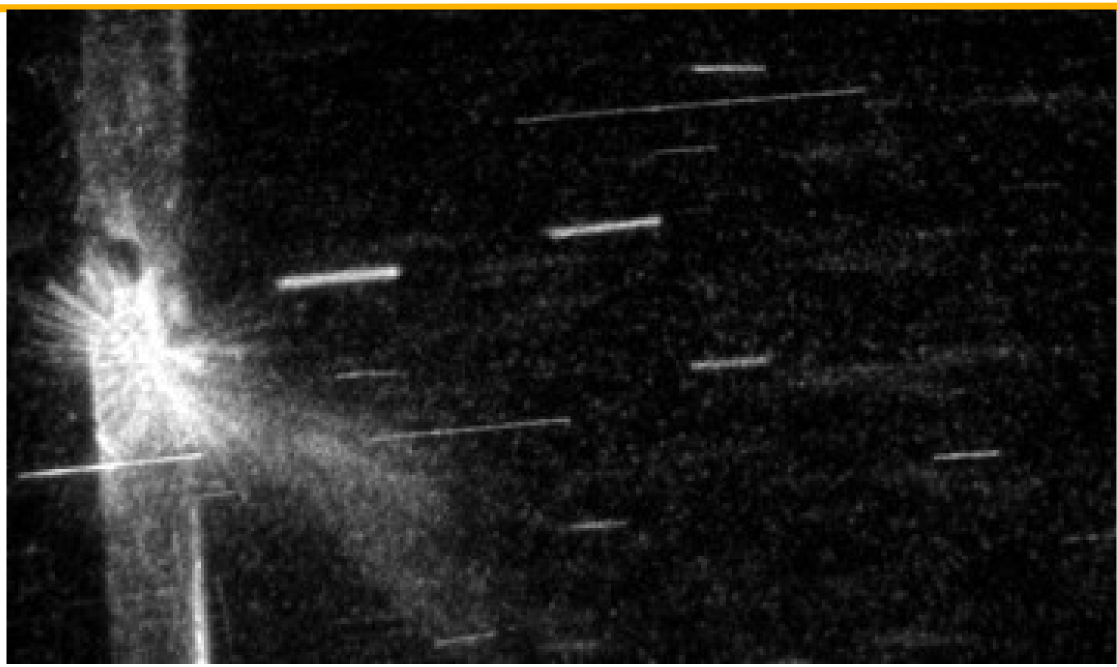




- graphite dust 1 to 44 μm (imaged grains >10 μm)
- ρd= 2.25 g/cm3
- Exposure 4μs
- Craters on dust catcher surface

Z. Wang, CM Ticos, GA Wurden PoP 2007
CM Ticos , Z Wang, G Wurden, IEEE Trans Pl Sc 2008

Dust collision with metallic plate



- Grain made of graphite shattered at the impact with metallic plate
- Exposure 12 μs

- Speed of flying dust grains (length of traces 0.7 cm to 3.7 cm): 0.5 and 3.1 km/s.

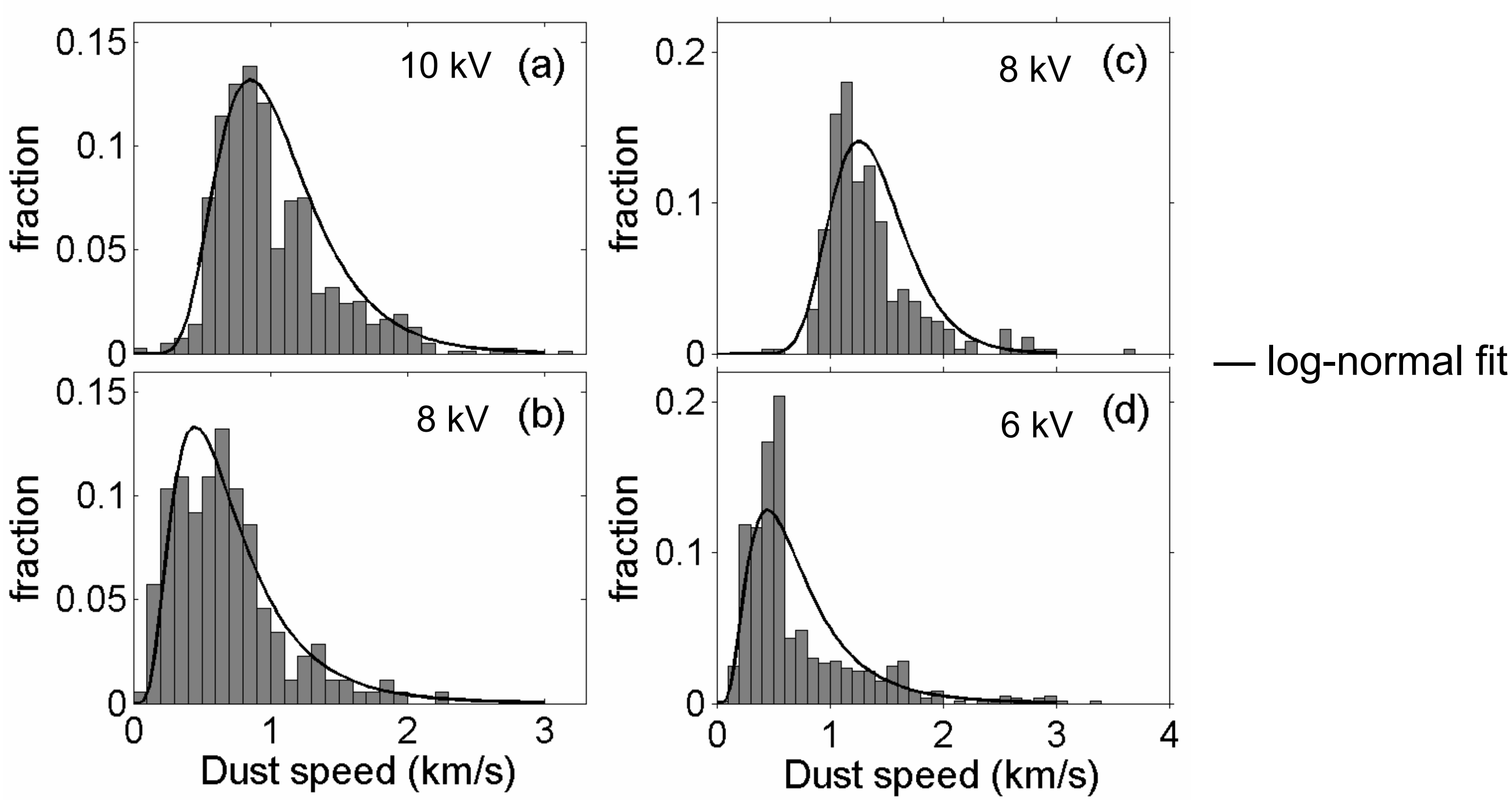
- Speed of flying debris : ~300-800 m/s.

Dust speed distribution

- vd= length of dust trace / image exposure

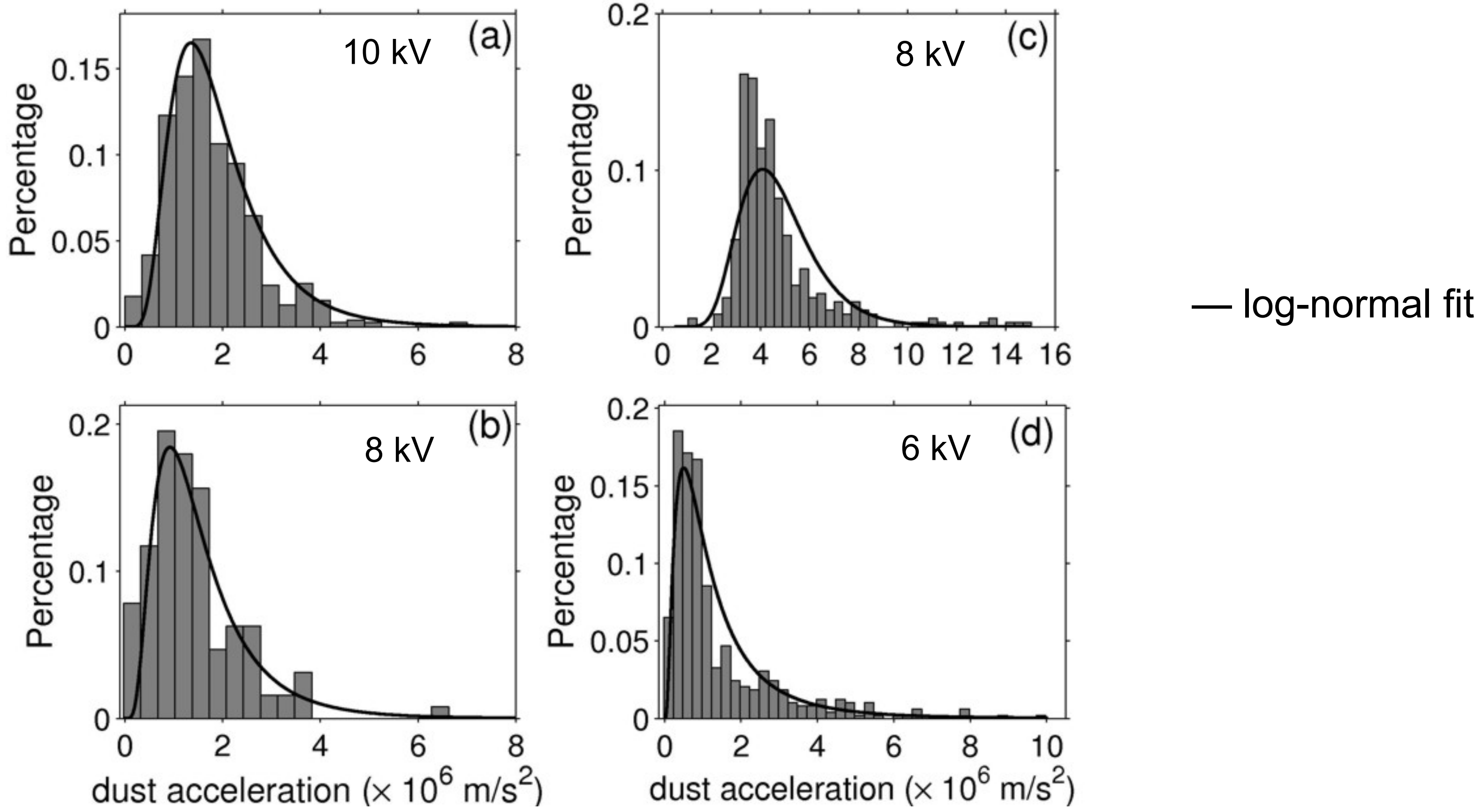
(a)&(b) Diamond dust

(c)&(d) Graphite dust



Dust acceleration distribution

- ad= dust speed / shot duration or
- ad= dust speed / time-of-flight if time-of-flight (200…400μs)<shot duration~400μs)



Dust charging in plasma

- Screening length $\lambda_D \approx 10^{-7}\ \mathrm{m} \ll r_d$ → sheath width s_d ~ a few λ_D
- Sheath limited theory (SL) to find dust potential V_d
- Ion current: $$J_i = \frac{1}{2} e n_i v_f \qquad v_f > \sqrt{\frac{k_B (T_i + T_e)}{m_i}}$$
- Electron current: $$J_e = \frac{1}{2} e n_e \sqrt{\frac{k_B T_e}{2\pi m_e}} \exp\left(\frac{eV_d}{k_B T_e}\right)$$ where V_d<0
- Current balance $0 = J_e + J_i + J_{therm} + J_{sec\_el}$ → $V_d \approx -1.5 k_B T_e$

($T_e = T_i$~1-3 eV)

Plasma drag force

- Supersonic flow→ expect collection radius $b_c \approx r_d$ (dust potential strongly asymmetric)
- Ion impact force *(Draine & Salpeter, AJ 79)*

$$m_d \frac{dv_d}{dt} = 2\pi r_d^2 k_B T_i n_i G_0(s) \equiv F_c, \quad \text{with}$$

$$s = \sqrt{\frac{m_i(v_f - v_d)^2}{2k_B T_i}},$$

$$G_0(s) = \left(s^2 + 1 - \frac{1}{4s^2}\right)\text{erf}(s) + \left(s + \frac{1}{2s}\right)\frac{\exp(-s^2)}{\sqrt{\pi}}.$$

- Electric force $Q_d E$

-Inductive E <10 V/m → $Q_d E$ small compared to F_c

-Electrostatic field $\perp v_d$

Heat flux to a dust grain

$$m_d c_d \frac{dT_d}{dt} = \Gamma_e + \Gamma_i - \Gamma_{se} - \Gamma_{th} - \Gamma_{rad} - \frac{\Lambda_s}{\mu}|\dot{m}_d|$$

$$\frac{dr_d}{dt} = -\frac{|\dot{m}_d|}{4\pi r_d^2 \rho_d}$$

- Electron flux $$\Gamma_e = 2k_B T_e \frac{|I_e|}{e}$$
- Ion flux $$\Gamma_i = (2.5k_B T_i - eV_d)\frac{I_i}{e}$$ → V_d -potential drop across dust sheath
- Thermionic electrons $$\Gamma_{th} = 2k_B T_d \frac{I_{th}}{e}$$
- Secondary electrons $$\Gamma_{se} = 2k_B T_{se} \frac{I_{se}}{e}$$

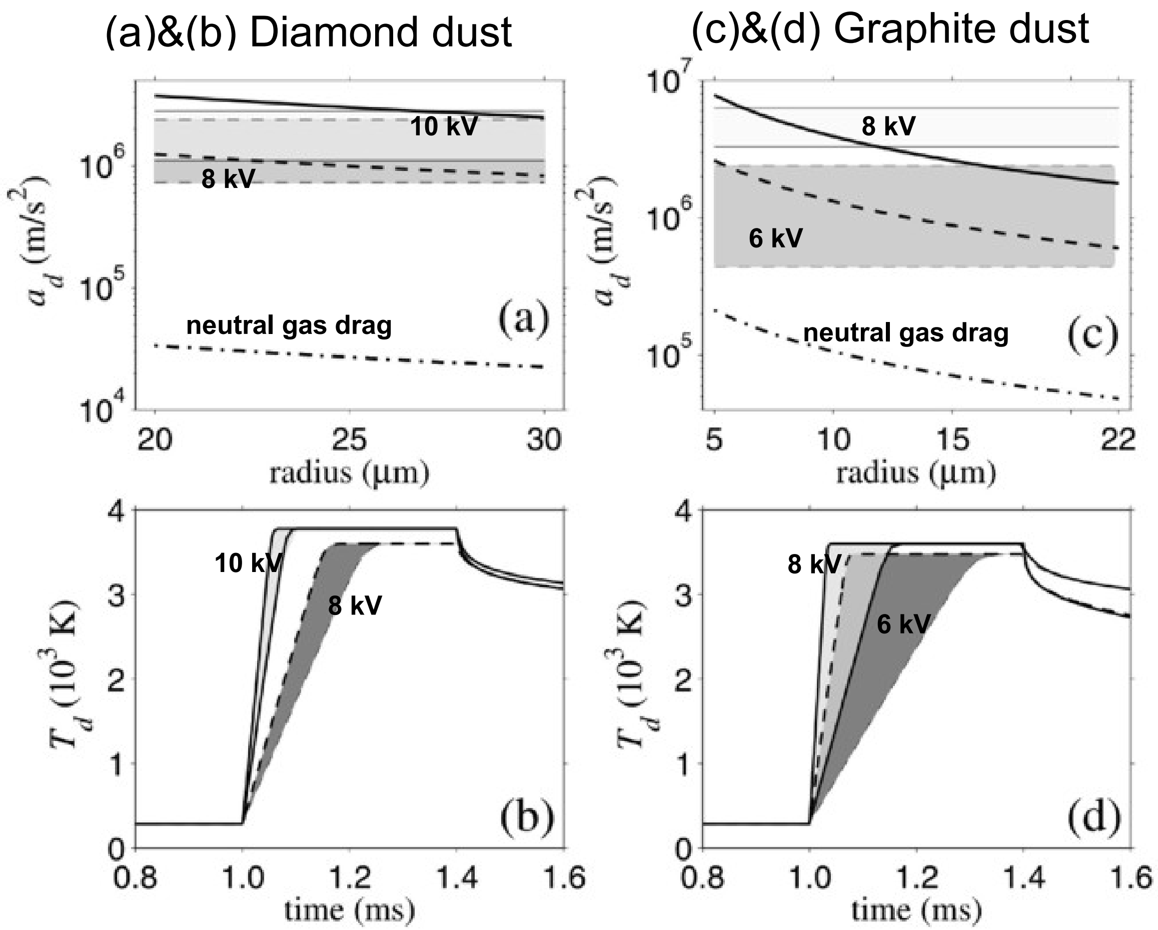
Simulation of dust acceleration

- grey bands:

range of measured a_d

- curves:

theoretical a_d using measured plasma parameters



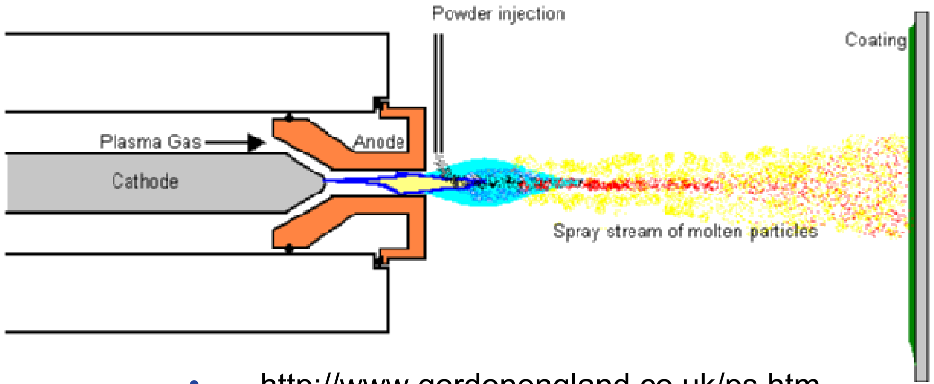
From 1…1.4 ms: dust heated and dragged by plasma

> 1.4 ms no plasma, radiative dust cooling ~ $\sigma(T_d^4 - T_{wall}^4)$

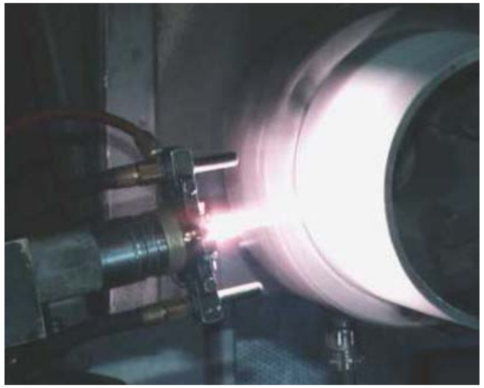
Applications of hypervelocity dust particles

- diagnostic of plasma flows, fusion plasmas
- quenching instabilities (ELMs) in fusion plasma (replacing puff gas, frozen pellets, or resonant magnetic field perturbations)?
- study of micro-meteorites impact
- space propulsion?
- Thin film deposition and coating of tools (thermal spray coating)

  - powder (TiC, TiN, WC, etc) fed into plasma flame (T~10,000 K) and accelerated to ~800 m/s



- http://www.gordonengland.co.uk/ps.htm



Conclusions

- Dust grains can be accelerated by plasma jets to a few km/s over ~1m

- Advantages of plasma acceleration:
  - -simultaneous for hundred grains
  - -1 order higher than compressed gas
  - -flexibility (grain material and shape, gas type, compact size, etc.)

- Better understanding of dust-plasma interaction is needed.

Thank You!