Dust Accelerators and Their Applications in High-Temperature Plasmas

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Dust accelerators and their applications in high-temperature plasmas

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Abstract

The perennial presence of dust in high-temperature plasma and fusion devices has been firmly established. Dust inventory must be controlled, in particular in the next-generation steady-state fusion machines like ITER, as it can pose significant safety hazards and potentially interfere with fusion energy production. Much effort has been devoted to getting rid of the dust nuisance. We have recognized a number of dust-accelerators applications in magnetic fusion, including in plasma diagnostics, in studying dust-plasma interactions, and more recently in edge localized mode (ELM)’s pacing. With the applications in mind, we will compare various acceleration methods, including electrostatic, gas-drag, and plasma-drag acceleration. We will also describe laboratory experiments and results on dust acceleration.
Outline

- **Applications of dust injection in high-temperature plasmas**
  - dust studies in magnetic fusion
  - calibration of diagnostics
  - benchmark of codes
  - mock-up experiments
  - plasma diagnostic applications
  - magnetic fusion (ELM pacing)

- **Dust acceleration**
  - Acceleration mechanisms
  - Comparison of acceleration schemes

- **Examples of recent laboratory progress**
  - Acceleration of dust to hypervelocities
  - Study of dust in flowing plasmas

- **Summary**
Dust generation in magnetic fusion devices

UFO's (NSTX)

TEXTOR-94

TFTR

Tore Supra

NSTX

Needs for dust measurement, dust physics
Matter injection is used to magnetic fusion & diagnostics in different ways

NSTX supersonic gas jet

Dust injection

Neutral beam injection

Pellet injection

There are plenty of gaps in-between

Size (μm)

0.001 0.01 1 100 ~500 1000
Necessity of hypervelocity dust for fusion diagnostics

Electrostatic shielding only

No electrostatic or cloud shielding

$R_{gr0} = 27 \, \mu m$

$n_{e0} = 2.0 \times 10^{20} \, m^{-3}$

$T_{e0} = 15 \, keV$

$v_{gr} = 180 \, km/s$

Normalized distance to the magnetic axis

minor radius $a = 0.52 \, m$
ELM's = Edge Localized Modes

(type III)

(type I)

Shot 124667

Shot 124664

(t=262.006 ms)

(t=262.007 ms)

(t=376.005 ms)

(t=376.004 ms)

(credit: R. J. Maqueda & NSTX team)
A brief summary of ELM's

- ELM is an periodic instability related to breakdown of H-mode edge transport barrier (pressure limit).
  - Many types: Type I, II, III, IV, V, ...

- ELMs appear as filaments, release particle and energy

- ELM related power load on diverter grows with machine size → ITER worse than existing machines.

- Type I ELMs (≥ 5 - 10 MJ/m²) should be avoided.
ELM's are similar to earthquakes

Richter scale = 5.2

scale = 7.8 (China, 2008)

\[ \Delta W_{ELM} \propto \frac{1}{f_{ELM}} \rightarrow \text{Increase } f_{ELM} \text{ to reduce } \Delta W_{ELM} \]
Pellet injector for ELM pacing

- Quasi-continuous operation.
- Minimizing ‘un-desired’ fuelling effect.
  - Small, slow pellets resulting in shallow particle deposition causing little fuelling.
- Different from the standard pellet injector for fueling:
  - High rep. rate ≤ 143 Hz
  - ‘Small pellet’ sizes, 200 -300 μm, icy D-‘dust’
  - Small pellet velocities 200 m/s (can not be lower than this)
  - Icy pellet sublimation → initial size ~ 2 mm
  - Pressurized gas as accelerating medium
  - 10 ms delivery time.
Dust injector for ELM pacing

- Electrosta
  - Particles
  - Electros (km/s) that
  - Both cold
    \ (~1000 H)

- Main adv:
  replaced by
  response, needed.)

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Electrostatic Particle Accelerators (\(< 1\))

- Limited to
- Not limited to
- Systems
- Injection
dust size-velocity for different applications

- Impact fusion
- MTF
- Diagnostics F
- Fueling
- Diagnostics E
- ELM pacing
- Dust in fusion

Dust radius (\(\mu m\)) vs. dust velocity (m/s)
Outline

• Applications of dust injection
  - dust studies in magnetic fusion
    - calibration of diagnostics
    - benchmark of codes
    - mock-up experiments
  - plasma diagnostic applications
  - direct fusion energy applications
  - magnetic fusion (fueling, ELM pacing)
  - Inertial fusion, innovation fusion concepts
  - impact fusion

• Dust acceleration
  - Acceleration mechanisms
  - Comparison of acceleration

• Some laboratory progress
  - Acceleration of dust to hypervelocities
  - Study of dust in flowing plasmas

• Summary
Dust acceleration overview

- Non-relativistic regime.
  - $2aL = U_d^2$.

- Acceleration ($a$) limit:
  
  
  $$ a = \frac{F}{m_d} = \frac{\sigma r_d^2}{m_d} \frac{\sigma}{\pi r_d^2} $$

  Offset yield strength

  Proportionality point

  Elastic point

  $\sigma_{max} \sim 10 - 3000$ MPa,
  steel 250 - 2500 MPa,
  polyprop True elastic point
  deuterium ice, 0.5 - 1 MPa

  $a_{max} \propto r_d^{-1}, 10^7 - 10^9$ g @ 100 μm

- Acceleration length $L$ for impact fusion!

Mechanical acceleration

- the 'simplest' scheme
- impact
- centrifuge
- Rocket effect

\[ U_d \sim 2V_0 \]

\[ \rho U_d^2 \leq \sigma \quad \Rightarrow \quad U_d \leq 1 \text{ km/s} \]

\[ U_d \leq v_0 \ln \left( \frac{M_0}{M_d} \right) \]
Neutral 'particle' acceleration

\[ F_{\text{drag}}(n) \]

\[ F(hv) = \frac{IA_d}{c}, \quad I \leq 10^9 - 10^{13} \text{ W/cm}^2 \]

(laser breakdown threshold)

- PdV,
  - gas guns
  - explosive accelerators
  - electrothermal accelerator

- Laser/light pressure
Charged particle acceleration

\[ \mathbf{F}_{\text{imp.}}(e^-, M_{i^+}) \]

- thermal plasma drag
- non-thermal plasma drag
- Charged particle beam drag

\[ \mathbf{F}_{\text{coloumb}} \]

Charged dust

(Harrison, 1967)
Acceleration by electromagnetic field

- Electrostatic acceleration
  \[ U_d = \sqrt{\frac{2q_d E L}{m_d}} \]
  - \( q_d = S_d \varepsilon_0 E_d \leq S_d (2\varepsilon_0 \sigma)^{1/2} \)
  - \( E \leq 10^7 - 10^8 \text{ V/m}, \text{ Modern RF resonator} \)

- Magnetic acceleration
  - cyclotron would not work (R too large)
  - magnetic materials (permanent magnets, superconductors)
  - rail guns (conductors, \( J \times B \))

- Electromagnetic (E&M waves)
Comparison of experimental results

- Solar meteorites
- Plasma jet
- Electrostatic
- Mechanical

(dust velocity (m/s) vs. dust radius (μm))
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Dust acceleration to km/s
Experimental setup for dust force study

[Diagram of experimental setup]

end-on view
Imaging of dust trajectories

A dust trajectory in 3-D

coaxial gun

one of the two views

Projection of the 3-D trajectory in the r-z plane, as in Fig. 5

Projection of the 3-D trajectory in the r-θ plane, as in Fig. 7
Comparison with models

\[ F_{pf} = 2\pi r_d^2 k_B T_e n_i \xi w \]

other forces are small
Summary

- 'The ultimate challenge'
  - impact fusion

- Near & intermediate term applications
  - Explore technological & applications of intermediate velocity (up to 100 km/s)
  - Dust transport study in magnetic fusion
  - Diagnostics
  - ELM pacing
  - ...

- Experimental results are reported
  - acceleration of dust cloud to km/s
  - Understanding of dust drag in flowing plasmas