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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.

**Keywords:** Dust, Accelerators, Plasma, Fusion

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## INTRODUCTION

The presence of dust in fusion machines is receiving increased attention from the plasma community [1]. Dust is produced in today's tokamaks and is a result of plasma-wall interactions, such as sputtering, arc melting of the machine walls surface, and condensation of impurities, or flaking of depositions, in particular, following a disruption or less violent but more frequent plasma instabilities, including Edge-Localized Modes (ELMs). The dust particles range in size from hundreds of nanometers to a few millimeters and have irregular shapes determined mainly by the formation process. Observation of dust is done "in situ" by high-speed cameras or at the end of a campaign, when it is collected directly from the walls of the machine. In the first case dust is self-illuminated as it is heated to high temperatures by the dense ion and electron fluxes and is transported by the cross-field flows. Dust is currently

produced in small quantities due to the relative small size of the current tokamaks, but in the next generation fusion machine ITER it can become a problem for the plasma confinement and for the safety of operations. On the other hand, the prospects of using a limited quantity of dust particles to perform diagnostics inside the fusion plasma or to control some type of instabilities are encouraging [2,3]. In this respect, it is desirable to select the dust material that is compatible with magnetic fusion energy production, control both the amount of the dust particles and dust speeds. Sometimes it might be necessary to have high speeds in order for the dust particle to reach further into the fusion plasma, near the core or at least way beyond the edge and the magnetic fluxes do not intersect with the fusion chamber wall.

### DUST ACCELERATION TECHNIQUES AND APPLICATIONS

A few successful techniques have been employed to accelerate micron-size dust particles to speeds of the order of km/s. Electrostatic acceleration relies on the electrical charge deposited on a dust particle by contact charging. A typical spherical dust particle exposed to a strong electric field (up to  $10^9$  V/m) created by a high voltage needle can reach the limit of elementary charges beyond which self-breakup can occur [4]. The highly charged dust particle is then introduced in a Van de Graaf accelerator and exposed to high-electric fields corresponding to voltages of the order of 1-5 MV [5]. This method is bulky and for higher speeds, multiple-stage acceleration is needed; however it is efficient and has been extensively employed to simulate micro-meteorites impacts with surfaces. The ultimate speed ( $u_d$ ) of the electrostatic acceleration is related to the dust sphere radius ( $r_d$ ) and the acceleration voltage ( $V$ ) as  $r_d u_d^2 = c V$ , with  $c$  being a constant determined by the material properties of the dust grain. Therefore, high speed ( $> 1$  km/s) is only feasible for submicron dust for a few MV of accelerating voltage. Still, this method is a "clean" method as no other material is mixed up with the dust particles at the end of the acceleration channel. Another technique is to accelerate the dust particles by puffing gas through a narrow nozzle in vacuum. The gas molecules or atoms flowing at the sound speed entrain in their motion the dust particles by transferring them their momentum through collisions. The drag force exerted by the gas is proportional with its density and the flow speed. The dust speed can in the best cases reach about 1 km/s since it cannot exceed the gas sound speed. Thus, the use of light gases such as H or He is preferred. However, the terminal speed can be greatly increased by the use of a piston put in motion by the high gas pressure which subsequently pushes the dust particles. This type of technology based on compressed gas has been developed and refined over the years resulting in the development of gas gun injectors

with multiple stages [6]. Millimeter-size pellets made of frozen ice have been launched at speeds up to 2 km/s for refueling tokamak plasmas. Heating of the compressed gas to about 450 °C has led to only a 10% increase in the terminal speed of the millimeter size pellets. An alternative technique which proved to be more effective in terms of attainable dust speed is based on dust acceleration by a dense plasma flow. A plasma jet is launched when currents of hundreds of kA flow between two coaxial electrodes for several hundred microsec, a center rod and an outer conductive cylinder. The self-generated azimuthal magnetic field and the current density produce a  $\mathbf{J} \times \mathbf{B}$  force which expels the plasma particles at about 10-60 km/s [7]. Dust particles released in the path the plasma jet are dragged in the flow direction, Fig. 1. The speed of dust particles measured *in situ* attained 3.7 km/s. The dust particles were made of carbon (graphite and diamond) compatible with fusion plasmas with a wide range of sizes, from a few microns to 60  $\mu\text{m}$ . Compression of the plasma jet in a helical coil improved the performance of coaxial plasma accelerators [8]. Dust particles speed of up to 20 km/s have been measured indirectly, from the length of the particles' trace in aerogels or from the impact force detected by piezo-electric probes. The mass of particles was in the range of  $10^{-10}$  to  $10^{-1}$  g. The drag force exerted by flowing ions and colliding with the dust particles is by far dominating dust dynamics at relatively high plasma densities of  $10^{17}$ - $10^{22}$   $\text{m}^{-3}$  [9], and is up to a factor of  $10^3$  larger than the force of gravity acting on a dust particles. High dust accelerations of  $10^7$   $\text{m/s}^2$  can be thus obtained on distances of the order of 1 m. One main drawback especially in fusion applications is the injection of plasma alongside the dust particles, which can mix with the fusion plasma and cool it down. Fast blocking valves can however reduce the effect of plasma flow leak into a fusion reactor. Table I gives the dust size range, the terminal dust speed, the acceleration distance and the main requirements of four dust acceleration techniques.

There are several applications of highly accelerated dust particles. The study of surface resistance to impacts with microparticles flying at several km/s is particularly important for space shuttles and satellites development. In material science, the morphological properties of some surfaces can be modified by bombardment with high speed nano or microparticles. In fusion plasmas, dust particles can be used for local magnetic field diagnostics by injecting a controlled amount and by further monitoring the spectral emission or by real-time imaging with a high speed camera the modifications suffered due to the interaction with the energetic plasma fluxes. It has been recently proposed to use highly accelerated dust particles for mitigating disruptions or local instabilities such as edge localized modes or ELM's in fusion plasmas [3]. Disruptions are large instabilities which terminate the discharge and put mechanical stress and heat on the machine walls. In the H confinement mode, several distinctive ELM types

were observed early. They included *dithering*, *type III* and *type I ELMs*. More ELM types have been found since then. The Type I ELMy H-modes show experimental performances that could meet the necessary requirements of a fusion reactor when extrapolated to the next step devices such as ITER. A major drawback of the Type I ELMy H-mode is the periodic (commensurate with the externally applied heating power) large power loads on plasma facing components (PFCs), in particular the divertor. ELMs have been observed to be triggered by fuelling pellets on several tokamaks, no matter where the injection location is. This led to the idea to artificially induce more frequent ELMs by injecting pellets smaller than what is usually used for fueling, the concept now known as *ELM pacing* [10]. It is possible to use dust injection to induce more frequent ELMs than currently possible with the pellet techniques. Based on our estimates, single dust (ranging from 50 to several hundred micron in size) injection at a frequency of  $\sim 1$  kHz and dust speed of up to several hundred m/s would be feasible.

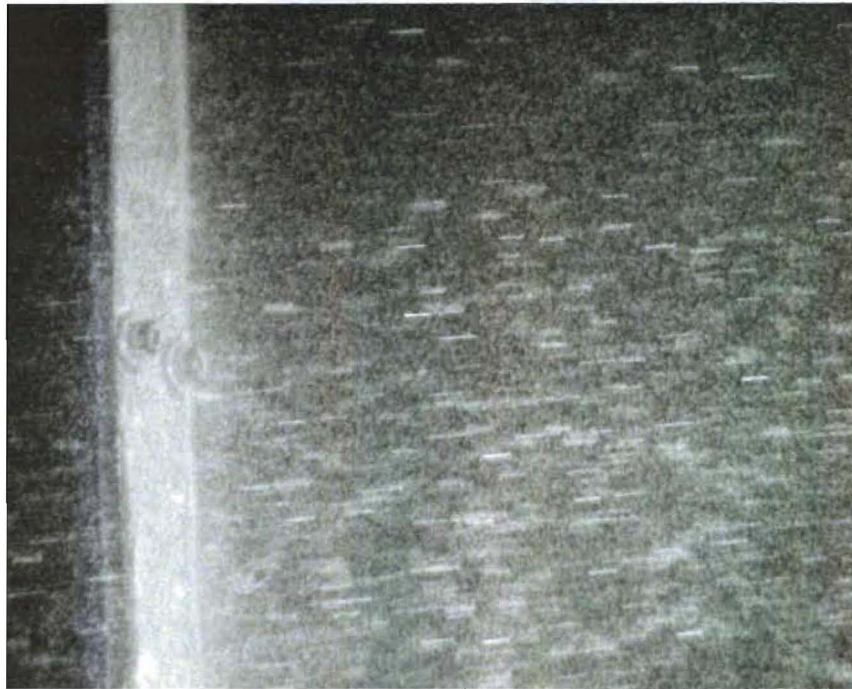
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TABLE 1. Comparison of different dust acceleration techniques

| Dust acceleration | Dust size            | Terminal speed | Distance              | Main requirements                     |
|-------------------|----------------------|----------------|-----------------------|---------------------------------------|
| Electrostatic     | 0.1- 2 $\mu\text{m}$ | 20 km/s        | $\sim 10\text{-}20$ m | Voltages 1-5 MVolts, $\sim 0$ current |
| Puffed gas        | 0.1-50 $\mu\text{m}$ | 100 m/s-1 km/s | $\sim 1$ m            | Gas pressure 10-100 bar               |
| Multiple stage    | 0.1-5 mm             | 2.5 km/s       | $\sim 5$ m            | Gas pressure 100-160 bar              |
| Plasma Drag       | 0.1-60 $\mu\text{m}$ | 3.7-25 km/s    | $\sim 1\text{m}$      | 10-50 kV, 10-300 kA (pulsed)          |

1



2

3 Fig. 1, A dust shower produced by a plasma jet. Each needle-like segment corresponds a high-speed glowing dust  
 4 grain of graphite. A probe is place on the left for reference. The exposure time is 4 microsec. The capacitor bank  
 5 charging voltage was 8 kV. Further details about the accelerator operation can be found in [7].