Dust as a versatile matter for high-temperature plasma diagnostic[a)]

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Dust varies from a few nanometers to a fraction of a millimeter in size. Dust also offers essentially unlimited choices in material composition and structure. The potential of dust for high-temperature plasma diagnostic is largely unfulfilled yet. The principles of dust spectroscopy to measure internal magnetic field, microparticle tracer velocimetry to measure plasma flow, and dust photometry to measure heat flux are described. Two main components of the different dust diagnostics are a dust injector and a dust imaging system. The dust injector delivers a certain number of dust grains into a plasma. The imaging system collects and selectively detects certain photons resulted from dust-plasma interaction. One piece of dust gives the local plasma quantity, a collection of dust grains together reveals either two-dimensional (using only one or two imaging cameras) or three-dimensional (using two or more imaging cameras) structures of the measured quantity. A generic conceptual design suitable for all three types of dust diagnostics is presented. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2953409]

I. INTRODUCTION

Many approaches to plasma (including high-temperature plasmas) diagnostics can be characterized as a method of matter-based interrogation. Examples include gas-puffing, neutral beam injection, heavy-ion beam injection, and pellet injection. Dust injection is less common. When broadly defined, dust includes small particles ranging from a few nanometers to a fraction of one millimeter in size, a factor of almost 10^6 in size variation. Both solid particulates and liquid droplets may be used. When taking into account of essentially unlimited choices of material compositions and structures, we may conservatively conclude that *dust-based* diagnostics (to distinguish them from *dust diagnostics*,[1] which are usually referred to methods that detect and characterize dust produced by plasmas) can have many possibilities and much potential for both low- and high-temperature plasmas. In the remaining text, we use the term dust-based interchangeably with *dust* for simplicity. "Archeological" dust-based diagnostics are possible when externally injected dust particles are collected and analyzed for changes due to exposure to a plasma. *In situ* dust-based diagnostics are possible when dust-plasma interaction is monitored in real time, mostly through detecting photons of different wavelengths that are generated by dust-plasma interaction. In some cases, the detailed understanding of dust-plasma interaction may not be required. On the one hand, developing new dust-based diagnostics is aided significantly by recent advance in the understanding of dust-plasma interaction, in particular, in high-temperature fusion plasmas. Such progresses have been partly driven by the need to better understand dust physics in fusion plasmas because dust has been recognized as a significant multifacet problem for future fusion plasmas. For this reason, diagnostic of dust in fusion plasma environment has become an increasingly important subfield of its own. On the other hand, new dust-based diagnostics of plasmas can contribute to both the better understanding of dust-plasma interaction and improved diagnostic of dust by providing experimental data that are more amenable to analysis and modeling when dust properties can be carefully chosen ahead of time.

Using dust to diagnose low-temperature plasmas was proposed before.[2–4] In low-temperature plasmas, the energy exchange between a plasma and a dust grain is usually small compared with the total energy required for the dust to undergo a phase transition. In high-temperature plasmas, the opposite is usually true. Dust in a high-temperature plasma usually exists only for a certain time before complete destruction.[5,6] Accurate description of dust dynamics and precise interpretation of dust measurements require more specifics of material properties in high-temperature plasmas than in low-temperature ones. Many forces affect dust motion. Yet the relative magnitude of the forces can vary in a high-temperature plasma compared with that in a low-temperature plasma. In particular, ion-drag force (or equivalently the plasma-flow drag in quasineutral plasmas) can become the dominant force in high-temperature plasmas when plasma density is sufficiently large. Furthermore, the dust temperature easily approaches its melting/evaporation/sublimation temperature in a high-temperature plasma, resulting in dust incandescence and emission of visible light, which can be detected with good efficiency and high sensitivity.

We describe dust spectroscopy to measure internal magnetic field of a plasma, microparticle tracer velocimetry

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(mPTV) to measure plasma flow, and dust photometry to measure heat flux. The three diagnostics are based on dust mass equation (mainly for scenario B as defined in the beginning of Sec. II), dust momentum equation, and dust energy equation, respectively. The lifetime of a dust grain (before full ionization) limits the time window for diagnostics. This window can be extended when diminished dust grains are replenished through continuous injection of new ones. Most discussions are limited to generic features of the diagnostics. Material-specific features of the diagnostics are left out for further work in the future when the dust properties are prescribed.

II. PRINCIPLES OF DUST DIAGNOSTICS

The following scenarios are possible when a dust grain interacts with a high-temperature plasma: (A) the dust remains roughly the same and (B) the dust changes dramatically until its complete destruction. In scenario (A), two regimes of dust-plasma interaction exist depending on the ratio of the dust size (r_d) to Debye length (λ_D).[7] In the so-called orbital motion limited regime, $r_d \ll \lambda_D$, long-range Coulomb interaction is important between a charged dust and charged particles inside a plasma, we refer to this regime as (A1). In the sheath limited regime, $r_d \geqslant \lambda_D$, a direct impact of plasma on dust is dominant, dust-plasma interaction is very similar to dust interaction with a neutral fluid, we refer to this regime as A2.

A couple of dust-based spectroscopic methods are possible. In one case [for both scenarios (A) and (B)], dust becomes the neutralization center of the plasma ions (including impurity ions). Spectroscopic methods are possible based on the neutrals generated by ion recombination on the dust surface. This type of spectroscopic method is similar to the charge-exchange recombination spectroscopy using neutral beams. In another case, primarily for scenario (B), neutrals (of the dust grains themselves) evaporate from the dust surface and can be used for spectroscopy, as discussed previously for internal magnetic field measurement in high-temperature plasmas.[8] In either case, dust is a source of neutrals and low-charge state ions for plasma diagnostics.

mPTV is based on the equation of motion of dust particles in a plasma,[7,9]

$$m_d \mathbf{a}_d = \mathbf{F}_{\mathrm{imp}} + \mathbf{F}_{\mathrm{Coul}} + Q_d \mathbf{E} + m_d \mathbf{g} + \cdots , \quad (1)$$

where $\mathbf{a}_d$ is the dust acceleration. On the right hand side, the first two terms are drag forces due to ion flows (or plasma flows in a quasineutral plasma). $\mathbf{F}_{\mathrm{imp}}$ is due to ions that directly hit the dust particle, $\mathbf{F}_{\mathrm{Coul}}$ is due to dust-ion interact at a distance (Coulomb interaction) since the dust is charged in a plasma. $Q_d\mathbf{E}$ is electrostatic force and $m_d\mathbf{g}$ is the gravity. Forces not explicitly written down can include radiation pressure, plasma gradients in temperature or density, thermophoretic force due to neutral particles, etc. In regime A2, however, we have identified a situation when $\mathbf{F}_{\mathrm{imp}}$ is the dominant force in sufficiently high density nearly fully ionized plasmas.[9] In this case, $\mathbf{F}_{\mathrm{imp}} = 2\pi r_d^2 k_B T_i n_i \xi \mathbf{w}$, where $\mathbf{w} \equiv \mathbf{U}_p / \sqrt{2k_B T_i / m_i}$ is the plasma flow velocity $\mathbf{U}_p$ normalized with ion thermal velocity. The other symbols are the Boltzmann constant k_B, the ion temperature T_i, the ion mass m_i, and the plasma density n_i. For subsonic flows, the coefficient $\xi = 1.1 - 1.5$ depending on the models for ion-dust surface interaction. We have neglected the dust velocity in $\mathbf{w}$ since dust velocity is a few orders of magnitude less than the plasma flow. This simplified form of Eq. (1) is the basis for mPTV.

Dust photometry is to measure the dust emitted electromagnetic spectra (ranging from infrared to ultraviolet) as a way to diagnose heat fluxes, including heat fluxes of electrons, ions, and electromagnetic radiation. The basic assumption is that emission spectra of dust particles are a function of dust temperature, which can be described by[5–7]

$$\frac{dH_d}{dt} = \sum_j Q_j + Q_\gamma \quad (2)$$

for dust enthalpy H_d. The summation Q_j is for *net* heat fluxes due to different particle species (electrons, ions, and neutrals) and Q_γ stands for the difference between radiative cooling and heating. For electrons, $Q_e = Q_e^{\mathrm{in}} - Q_e^{\mathrm{out}}$, where Q_e^{out} is a summation of secondary electron emissions due to ion impact, secondary electron emission due to energetic electron impact, photoelectric emission, and thermionic emission.[7] For ions, $Q_i \sim Q_i^{\mathrm{in}}$ in cases when neutralization happens at the dust surface for incoming ions and each ion leaves as a neutral particle. Corresponding to the ion-neutralization scenario, the neutral fluxes play the role of cooling primarily, $Q_n \sim -Q_n^{\mathrm{out}} = -\delta Q_i^{\mathrm{in}} - \Lambda / \mu_d |m_d|$. Λ is the heat of vaporization and μ_d represents the molar mass, both of which are intrinsic to the cooling and dust mass loss $|m_d|$. $0 < \delta < 1$ is the fraction of ion neutral recombination at the dust surface. $Q_\gamma = S_d q_\gamma$, S_d is the dust surface area, $q_\gamma = \sigma(\varepsilon T_b^4 - a T_d^4)$.[2] σ is the Stefan–Boltzmann constant, ε is the dust emissivity, T_b is the effective ambient temperature, a is the dust absorptivity, and T_d is the dust temperature. The time for dust temperature to equilibrate (τ_d^T) is proportional to the dust size, $\tau_d^T \propto r_d$; therefore, only the largest dust grains (>100 μm) can have a nonuniform temperature across the dust body. We can treat most dust particles as isothermal objects with a well-defined temperature T_d.[2,5] Apparently, interpretation of dust temperature change in general requires sophisticated physical models, which is still an active research front.

In a simple case when the dust mass change is small, i.e., $dH_d/dt = m_d C_d dT_d/dt$ for dust heat capacity C_d, two types of heat flux measurement exist based on the temperature change. One case is when the heating is dominated by ion flux, $m_d C_d dT_d/dt \simeq \Theta_i Q_i^{\mathrm{in}} + Q_\gamma$. This situation is similar to that in low-temperature plasmas, where the factor Θ_i reflects the fact that ions gain energy from the dust sheath. Another case is when the heating is dominated by electron flux, $m_d C_d dT_d/dt \simeq \Theta_e Q_e^{\mathrm{in}} + Q_\gamma$, where Θ_e is a corrective factor for out-streaming electrons. Out-streaming of electrons reflects the charge balance on the dust even in the electron-dominated heating regime. The transition from ion-dominated heating to electron dominated heating is shown to exist theoretically for edgelike plasma conditions in a fusion device.[7] Basically, the thermionic and photoelectric emissions of electrons are sufficiently enhanced so that the floating potential of the dust can be close to or even above the local plasma potential and the dust draws predominantly

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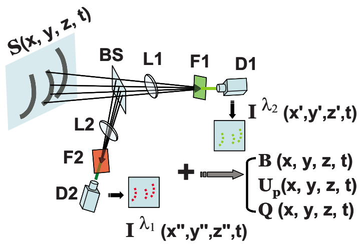

FIG. 1. (Color online) The schematic setup of a generic dust imaging system for dust spectroscopy, mPTV (only uses one arm, therefore no BS is needed), and dust photometry. Use of different filters (F1, F2) in the two arms will lead to measurement of different plasma quantities such as magnetic field (**B**), flow ($\mathbf{U}_p$), or heat flux (**Q**).

electron heat flux. Ion heat flux measurement can be realized using relatively large dust, while electron heat measurement can be done using smaller dust, when dust approaches its melting or sublimation temperature.

III. A GENERIC CONCEPTUAL DESIGN

Even if the initial velocity of a dust grain is small, the dust particle can pick up significant velocity up to a few hundred m/s at the edge of a fusion plasma device.[10,11] Correspondingly, dust particles can travel tens of cm during a few ms. Therefore, a dust diagnostic must generally have an imaging system which covers a rather broad field of view. Meanwhile, detector size is a limiting factor for spatial resolution. The combined requirements of large field-of-view and miniature detector size necessitate the use of two-dimensional (2D) arrays of many detector cells for dust imaging. A benefit of using 2D detector arrays is that multiple dust can be tracked simultaneously. Examples of imaging systems to visualize dust plume were given earlier.[9,10,12] Besides imaging system, another main component of a dust diagnostic is a dust injector,[13–15] we limit this discussion mainly to imaging systems.

A generic conceptual design for dust imaging with a pair of 2D imaging arrays (D1 and D2) is illustrated in Fig. 1. When dust particles are injected into the plasma, they turn hot and emit a spectrum of electromagnetic radiation,[9,10,15] designated as S(x, y, z, t) in Fig. 1. A beam splitter (BS) is used to split the signals into two arms, each with lens (L1, L2) and spectral filters (F1, F2). This conceptual design can be used for dust spectroscopy, mPTV, and dust photometry. The key differences are in the filter characteristics, as summarized in Table I. For dust spectroscopy, good resolution of wavelengths is needed for Zeeman splitting and thus magnetic field measurement. We can use a pair of narrow pass-band filters.[16,17] The center wavelengths of the filter pair are $\lambda_0 \pm \delta\lambda$, The transmission functions of the filter pair are $\pm dT_0/d\lambda$ ideally, i.e., one with a positive slope around λ_0, the other with a negative slope around λ_0. The ratio of the two transmitted light intensities gives the wavelength shift, which can be converted into magnetic field. For mPTV, we do not need the BS and only one narrow line filter is needed for one arm. Narrow line filter may give us better signal-to-noise (background radiation) ratio.[9] For dust photometry, two band filters may be used. Each centers around a different wavelength: λ_0, λ_1. It is conceivable that additional filters at other wavelength bands may be needed to accurately measure dust temperature since dust may not be like a blackbody; if so, one may use additional BS to accommodate more filters and imaging arrays. The bandpass filters should be chosen to avoid the strongest lines of the ablation cloud (if such a cloud exists). Setup like Fig. 1 only measures a 2D projection of a three dimensional (3D) field of magnetic field or plasma flow or heat flux. For a 3D measurement, we need at least another view with a different angle of observation. We can use the same setup for the new angle, preferably a 90° angle.

TABLE I. Different characteristics of the filters used in dust spectroscopy, mPTV, and dust photometry. More details are given in the text.

Diagnostic	Filter center wavelength (s)	Important filter feature
Spectroscopy	$\lambda_0 \pm \delta\lambda$	Transmission slope
mPTV	λ_0	Line filter
Photometry	$\lambda_0, \lambda_1, \cdots$	Band filter

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