

Critical review of complex plasma (dusty plasma) diagnostics and manipulation techniques for the fusion community and other

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Abstract

This review surveys the present state of the art of diagnostics and removal techniques for particles suspended in plasma. Research on “Dusty Plasmas” is necessary for ITER and the fusion reactors of the future. The aim is to transfer the knowledge acquired in complex (dusty) plasma research and in the low temperature plasma community to the broad fusion community, which is being mobilized to understand/quantify this phenomenon and find solutions. The introductory style makes it accessible also to safety personnel and other interested readers with only basic knowledge of plasma. In the transfer from research to technology we have tried to assess the applicability of the methods proposed and we have identified further, much needed, R&D.

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INTRODUCTION

The formation of dust in plasmas has always been one of the main problems of plasma processing of materials and semiconductor technology. Several, consecutive, solutions to the problem, although partial, have allowed the technology to proceed further towards smaller feature and faster processing. The formation of unwanted dust in plasma is also a problem in the realization of a fusion reactor which will have to operate in long pulses and eventually in steady state. An initial study of the behavior of dust in Tokamaks is reviewed in [1]. Large quantities of dust may be formed in the Scrape Off Layer and in the divertor region as a result of the power flow to divertor. In ITER dust generation rates are estimated to reach the upper limit of: 100 kg of W, 100 kg of Be and 200 kg of C [2] already in the early experimentation (500 plasma power pulses). ITER has defined a strategy that foresees the development and validation of a model for dust production rate, the development of diagnostics and removal techniques with final validation during the first hydrogen phase of ITER from 2016. In this context the fusion community is starting to consider diagnostics of dust in plasma, during plasma pulses and electrostatic/plasma methods to lift the dust in non-operating times. The way is to track the dust formation/behavior in presently operating machines and compare the results with theoretical models of dust transport and removal, which will be in parallel validated in small laboratory experiments. Those models will be then ready to predict the behavior of dust in ITER.

The dust accumulation has safety aspects, because of the extremely large surface that exposes the material to quick energy release in case of reactions, and because nano-sized dust can be a route for the dispersion of radioactive material, material activate by fast neutrons, in case of accident, or simply not retained by the pump filters. An additional problem is the tritium retention by the dust. Dust presents a large surface to plasma and is easily loaded by the energetic ions. Other unwanted dust consequences could be the shorting of coils or other biased surfaces by metallic dust and the occlusion of optical diagnostics. The formation of dust from erosion of the most exposed part of the machine is a topic of interest to all community studying the plasma-wall interactions. The re-deposition, in form of co-deposited layers or dust, has negative consequences. The physics of the tokamak is modified by dust too. There is evidence that the presence of dust affects the MHD behavior of the Scrape Off Layer mainly through modifications of the ions and electrons energy distribution functions [3 - 7]. Grains, hardly affected by the magnetic field, can travel into the SOL in the solid or liquid state as far as to the separatrix [8]. Their evaporation will provide a dangerous source of high z impurities so degrading the plasma border quality.

The control of the dust is still a non-solved issue, in particular because dusty plasmas, or with a more academic definition, complex plasmas, is a new field and many interrogatives have not yet find a solution at the fundamental level. Fine dust (for which the gravity is ignorable against the plasma confinement of the negatively charged dust and momentum due to radiation/particle flows) is still largely unpredictable; to give an example we can only guess the accumulation points in tokamaks. Other forces experimentally observed drive the suspended particles towards potential gradient. In ITER dust may accumulate in the gaps between blanket modules and in the gaps of “macrobrush”. Dust can be in presence of weak secondary discharges under the divertor dome. The large range of order of magnitude involved, from nanometers to millimetres for the powder are an added complication. The available theoretical instruments of modeling the transport still have to be validated in a variety of challenging fusion reactor environments. It is clear the need of

developing adequate diagnostics during the plasma phases, operations or glow discharge cleaning, in the framework of a coherent research and development program.

The removal of dust during the plasma phase presents advantages with respect to the collection of the dust fallen over large areas and often accumulated in hidden and awkward places, thus avoiding building up of large quantities. Under vacuum and in absence of plasma, the proposed techniques, mechanical broom or laser ablation, must be scanned over large surfaces by remote handling. In air dust can be vacuum cleaned and particles in small interstices can be removed by compressed gas. However, nano-particles will still escape from filters and the venting opportunities are anyways too rare to avoid accumulation. Instead, during the plasma phase dust is extremely mobile and can be guided to selected points to be extracted. Nano-particles can be aggregate together to more manageable sizes.

This review propose methods of diagnostic and removal, developed in the complex plasma community for research of fundamental character and in the low temperature plasma physics for controlling the plasma processing. The aim is to avoid a duplication of effort. It must be pointed out though that the transfer of the knowledge will not be straightforward and will require still a good deal of R&D. Some relevant possibility of research, from fundamental to applied and technological is indicated a side of the review, in the following text

PART 1: INTERACTION OF SMALL BODIES AND PLASMA, CHARGING AND TRASPORT

The subject to be studied is the general behaviour of dust particles in plasmas and in space-charge sheaths. The this review the term ‘dust’ is used to indicate solid or liquid aggregates of material of dimension larger than that of the single ion or atom or molecule or radical presents in plasma. Dust may be generated by the agglomeration, or the growth of components of the plasma. Sometimes these plasma constituents include material sputtered from the electrodes or from the wall and not inserted in the chamber in the gas mixture. The particles become “dust” when they acquire a charge which is not strictly related to the valences of the original constituents. The lower dimension of a particle is of the order of one nanometre while atoms, molecules, radical and ions are in general up to one nanometre. In our case ‘dust’ go from nanometre size up to millimeters, in special occasions.

Several reviews of the effects quoted below are available in ref. [9-15]; experiments are reviewed in [10, 11 and 14]. Dust particles in plasma acquire an electric charge due to absorption of plasma electrons and ions. The flux of electrons to the particle is usually the larger because of their smaller mass. They quickly pick up energy from the field and have higher thermal motion, even when their energy is equal to the energy of the ions. The equilibrium charge is hence negative in the great majority of the cases. Low energy electrons are repelled and ions are accelerated towards the small body in a region next to the particle called sheath; here the space charge is positive to screen the negative charge of the body surface. The negative particles are confined in plasma by the plasma sheath; the walls, being effectively planar geometry, are even more negative than the dust particles. When electron emission processes are present (due to UV irradiation, thermal or secondary electronic emission, radioactive decay) the charge can be reduced in absolute magnitude or even become positive, in particular during transients, or as effect of fluctuations. The particle then drifts outside the plasma, even against gravity. Charged

particle interacts with other particles and with electric and magnetic fields as well as with surrounding plasma. Even at the level of the most elementary interaction the charge of a small body in plasma is one of the important questions not yet fully resolved in the physics of complex plasmas. Previsions are heavily dependent on the assumed hypothesis for the ion motion to the particle; it can be orbital for long mean free path, or radial in presence of few collisions. Most of theories operate in stationary homogeneous quasi-neutral plasmas. However, much more complicated theories for the ion kinetics in large electric/magnetic field, where the central force field hypothesis can not be applied, should still be developed.

Dust particles grow in the plasma, from atoms and radicals produced by sputtering, through the way nucleation-aggregation-deposition (for carbon see [16]), or are the result of detachment of co-deposited layers or fragment of the surfaces exposed to plasma. They diffuse in plasma under the influence of several forces, the most important being electrostatic forces, particles' drag, thermophoresis, plasma anisotropies and directed radiation pressure. On a large time scale (say \sim seconds), particle in the SOL or divertor tends to segregate themselves in equilibrium loci, where all the forces are compensated; also in time dependent effects, turbulence or ELMS, all dust reacts homogeneously. Increasing particle density, inter-grain forces begin to be important and homogeneous, well distinct, assemblies form, separated by charge double layer. In equilibrium these assemblies are stratified. For particle of dimension $\approx \geq 1\mu\text{m}$ gravity can be balanced only in small regions of plasma (especially in the so called sheath region of discharge) where the quasi-neutrality is violated and the corresponding electric field is sufficient to levitate the dust particles. Other forces may also play a role. Momentum (or energy) transfer from plasma to one particle's surface can produce a net attractive force on another particle situated nearby. This effect is known as shadow effect and has been successfully verified in microgravity conditions. Another force leading to the formation of coherent dust assemblies is dipole-dipole interaction. Dipoles are due to an elongation of the screening charge (screening cloud) because of directed ion motion, external fields, asymmetries and other.

The continuous absorption of reactive species on the dust particle surface, which is essential to maintain the equilibrium charge, introduces many new effects with respect to two-component plasmas. The electron and ion distribution functions diffuse in energy, their density distributions around the grain deviate from the Boltzmann law and the screening can substantially deviate from the Debye form.

Dusty plasmas are characterised by several parameters:

Density of the dust

Charge

Coupling parameter (ratio of the particle-particle interaction to their thermal energy), controls largely the state of aggregation of the particle assembly, crystal, liquid...

Havnes parameter (ratio of the particle surface charge to the free electrons negative charge) controls all the fast behaviour, waves, transients, etc.

Interaction parameter, the ratio of the inter-grain distance to the Debye length, when low the sheath may collapse and particles stick together.

Velocity, thermal and directed

Dispersion in size, shape or equivalent surface

Material properties: material, density, porosity, permittivity, susceptibility, state of aggregation and other.

Temperature (kinetic of the grains and of the surface, vaporisation...)

These parameters should be assessed by the diagnostics in order to plan an efficient removal. The diagnostics must space-resolved as in a certain region of plasma/plasma sheath the particle assembly is quite homogeneous but, as already mentioned, “stratified”.

PART TWO: DUSTY PLASMA DIAGNOSTIC POTENTIAL FOR ITER

1) Visualisation, light scattering

Dust in tokamaks may have a huge range in dimension, from few tens of nanometres to millimetres. In principle the techniques described below scales with the ratio of the dimension to the wavelength of the radiation, however sources of radiation are limited. Also, note that the theory, at the state of the art, considers almost only mono-dispersed spheres, and the determination of the particle size in non-spherical and size-dispersed assemblies is still a critical issue.

Rayleigh scattering is applicable when the radius, r , of the scattering sphere is much smaller than the wavelength, λ , of the incident light. For example, for red light ($\lambda \sim 0.65 \mu\text{m}$), calculations using Rayleigh scattering for $r < 0.01 \mu\text{m}$ are essentially identical to the rigorous results obtained using Mie theory. Rayleigh scattering shows a strong dependence on λ , i.e. λ^{-4} . The intensity for perpendicular polarisation is independent of scattering angle - whereas the intensity for parallel polarisation varies with scattering angle with a minimum at 90° . In contrast to Rayleigh scattering the Mie solutions to scattering includes all possible ratios of diameter to wavelength, although the technique results in numerical summation of infinite sums. In its original formulation it assumed a homogeneous, isotropic and optically linear material irradiated by an infinitely extending plane wave. However, solutions for layered spheres are also possible. Unfortunately, the infinite series which must be evaluated exhibits inconveniently slow convergence. In fact, to obtain accurate results for a sphere with a size factor $x=2\pi r/\lambda$ approximately x terms must be evaluated. Practical evaluation of these series must therefore be undertaken with the aid of computers. Even then, however, a calculation using the Mie theory as currently formulated becomes less and less practical for $r \gg \lambda$. See ref. [17-23]

In tokamaks an initial guess of the dimension could be done measuring the backwards scattering at different wavelength or the polarisation at 90° . To give an example we consider a region of plasma with suspended dust fairly large, of the order of 100nm or more (particles larger than 10-20 μm are likely to fall down). This dust would give a Rayleigh scattering to an IR laser light and MIE scattering to a near UV laser. The ratio of the scattered to forwards power at a large angle, near 180° would

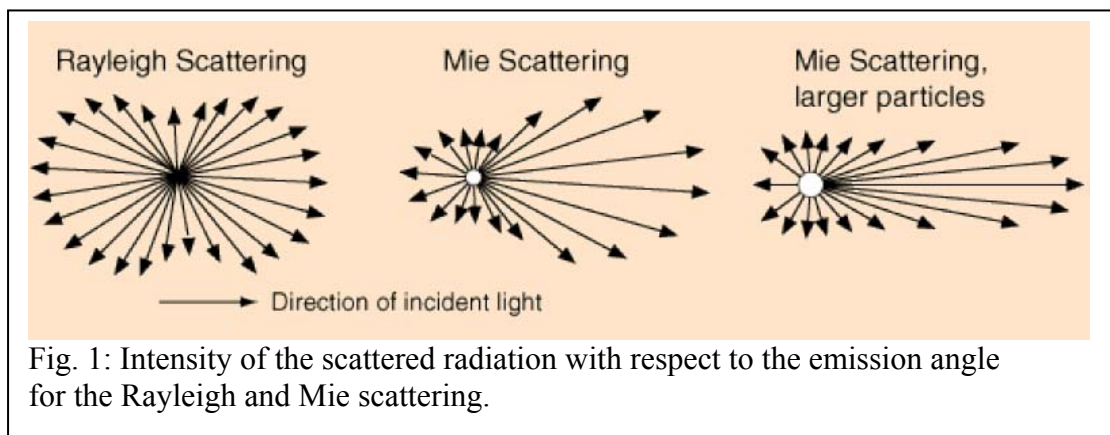


Fig. 1: Intensity of the scattered radiation with respect to the emission angle for the Rayleigh and Mie scattering.

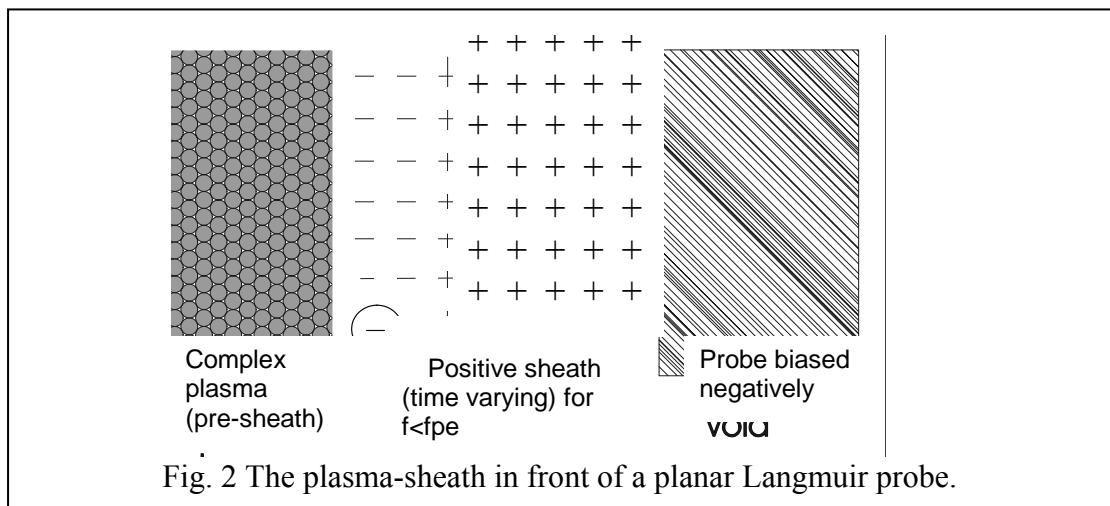
be very different, see fig. 1. The same can not be said for small dust, of the order of 10nm. Although this measurement can provide only an order of magnitude of the size, it is very easy to install and require only one large port to allocate together laser beam and detector. Some work in this direction has already started but the development needs a good amount of R&D, as laboratory calibration and injected particles of controlled size, in tokamaks, in particular for highly dispersed, irregular size dust.

A topic not much covered in literature is the difference between optical methods applied in a plasma environment with respect to the same methods applied in gas. Further study should deepen the understanding of the Debye scattering, ref. [24]. This is the scattering of electromagnetic waves by the Debye shielding cloud of the charged dust. The shielding cloud can be seen as a “bubble” for the electrons, so creating a discontinuity of the permittivity at a distance of the order of the Debye length from the solid surface of the grain. For dielectric dust this discontinuity is larger than that between the sheath, almost void, and the solid surface. Possible a systematic error is introduced when the Mie scattering is used to measure the diameter of dust particles in plasma. The same reasoning may apply also for the Rayleigh scattering, however the floating potential (roughly proportional to charge) of particle with small r/λ_D ratio is less important and so is the screening. The above problematic could justify a broad programme of research, that would have fundamental aspects in parallel to fusion technology applications.

Here we add a note on the technical implementation of these diagnostic techniques. The gravity will be more and more important as the dust radius grows. The weight will push the particle assembly downwards where stronger electric fields develop at the edge of the plasma. If the Mie/Rayleigh scattering is observed with the laser normally used for Thompson scattering, the detection of dust is related to the position of this beam in the chamber. The probability to find dust is much higher in the lower SOL or divertor, when the divertor is at the bottom. See also table I

2) Langmuir probes

Langmuir probes are already utilised as a standard diagnostic in fusion machine. However the interpretation of the characteristics in presence of dust has to be modified due to a non equal density of electrons and ions at infinity. This because part of the negative charge of the plasma is bond to the surface of the grains, see fig. 2. The I-V characteristics clearly show electron depletion; however, like for electronegative plasmas, the positive ion flow to the probe is modified too (pre-sheath



and Bohm criterion are modified, ref. [25]. The main consequence is that n_e/n_i can not be derived from the ratio of the saturation currents. A comprehensive theory is at the moment still in development. To test this theory we would like to conduct laboratory experiments with known size injected particles ~ 1 μ m. However this size dust is stratified in layers of different q/M (balance of electrostatic to gravity forces) the thickness of which is lower than the perturbation introduced by the probe, the probe sheath, see ref. [26-28]. Another possibility would be to test probes in plasma-grown nano-particles, as at the initial phase in Tokamaks, but this diagnostic should be associated with light scattering and/or free electron detection to have a complete picture (the quasi-neutrality equation for the complex plasma is:

$$n_i = n_e + z_D n_D \quad 1$$

with z_D the number of electrons on the grain and n the density for electrons, ions and dust).

The dynamical behaviour is modified too. Dust grains have inertia and find their equilibrium position around the negatively biased probe for frequency of the ramp up to the dust plasma frequency:

$$\omega_{pD} = \left(n_D e^2 z_D^2 / \epsilon_0 m_D \right)^{1/2} \quad 2$$

Here m_D is the mass of a dust grain and ϵ_0 is the permittivity. Above this frequency the dust particles are stationary at an averaged distance. In an experiment with probes negatively pulsed it would be possible to see an increase of the ion saturation current in a time scale of the order of microseconds for the ion motion and another increase, on a time scale of $1/\omega_{pD}$, due to the expanding boundary of the dust cloud.

For transient, like a passing by particle several effects should be taken in account. The charge induced on the probe is by far too small to be seen, ref. [28], but the effect of the perturbation of the screening is detectable. The charge transferred in an impact may induce a large spike of current [29]. A triple probe [30] is suitable to study this type of transients because it is steady state. An array of probes would provide modulus and direction of the motion.

To summarise the work on probes we should distinguish the work in steady state operations, or almost steady state, in which the ratio of the saturation currents, together with the inertia properties could provide an indisputable signature of the presence of dust, and transient phenomena. These latter are, at the moment, still to be characterised. Their time behaviour, as intensity and shape of the perturbation, is probably much different from perturbation related to density fluctuations, energy fluctuation, periodic turbulences and other. See also table I.

Table I The proposed diagnostics with feasibility in principle in the ITER environment

Diagnostic\ feasibility in ITER	Feasibility	Technical requirements	Compatibility vs radiation, fields and temperature	Information achieved	Need more R&D
Visualisation, light scattering	Yes. To monitor the huge range of powder dimension several lasers are needed $100\text{nm} < \lambda < 1\mu\text{m}$	At least two ports at an angle $> 90^\circ$	Yes, non invasive	It may be possible to derive density and radius of the dust in suspension	Yes, for non spherical shapes, dispersed assemblies, etc. Debye & collective scattering
Langmuir probes	Yes. In particular if probes are already planned	Triple probe (transients) variable ramp for measure of the dust inertia	Only in places where the power input is limited.	It may be possible to monitor the presence of dust, ni/ne and q_D/M_D	Development of the theory and study of transients
Grids-electrostatic techniques	Useful for calibrations but not suitable for tokamaks env. Invasive, unless mounted on the walls.		Only in places where the power input is limited.	Integral measure of the radius: $r > \text{spacing}$. Dust flux	The relation between dust flux and dust density should be studied
RF impedance	Yes, even if this diagnostic is less developed than others. Can be coupled with the RF removal device	One or two electrodes on the wall facing possible dusty plasma	Should not overlap with existing RF (in this case analysis of harmonics can give info without extra devices)	Electromagnetic properties of the dust cloud at high frequency	Study of the possible path for the RF current in presence of different complex plasma
Velocimeters	As visualisation. Light power should be enough for the N_{frames}/s but not to perturb the system	As visualisation + fast data acquisition and memory store	Yes	Velocity of the particles at least in 2D (directed motion)	More research on the technology of 3D systems
Temperature	Only pyrometric methods are possible in ITER	One port with line of sight to the dusty region	Yes	Temperature and aggregation state of the dust.	To relate the temperature to the environment, degassing of the tritium, vaporisation...

3) Grids-electrostatic techniques, energy-mass analysers

Electrostatic detectors may consist in two interlocking traces suitably spaced and exposed to a dusty environment [310]. When the traces are biased and a conductive particle, with diameter larger than the spacing, shorts the circuit a pulse of current is detected. The particle evaporates with a time related to its mass. This kind of machine can work in plasma or in gas and in vacuum. However the interpretation of the results is much different in these three cases because the pulse counting is proportional to the density of the particle in the unperturbed medium multiplied by the velocity of the particles to the devices. In plasma the plasma sheath in front of a positive surface is extremely complex [32,34] and the plasma sheath may be comparable or even larger than the spacing. In gas the random flux to the device is given by: $v=(kT_e/2\pi m_D)^{1/2}$ where the temperature of the dust is strongly dependent on the neutral drag, i.e. base pressure. In vacuum there should be no dust suspended. This technique is likely to be invasive.

Other electrostatic diagnostics, as the retarding field energy analyser [35, 36], or deviation energy analysers can detect dust in a similar manner as Langmuir probes with the great advantage that they can be mounted on the wall. No previous work on the use of these diagnostic in a dusty environment is available at the moment. In tokamaks the analysers should be placed at the points of aggregation of the dust, as in the lower part of the vessel and/or in vicinity to potential discontinuities etc. In the same position ad-hoc build mass analysers may detect the residual charge on some particles of intermediate size, q/m scans from 10^5 on nanoparticle (with $q = 2-3e$ and 300 C atoms) to one, on micro particles ($q = 1000e$ and mass $10^{-14}kg$). The magnetic field of the tokamak itself could be exploited; we would look for frequency resonances and power adsorption.

In summary energy and mass analysers are promising techniques notwithstanding a lack in previous research towards dust detection. They are standard machine; however their dimension should be matched for the specific application. See also table I

4) RF impedance

This new diagnostic consists in applying an RF voltage, of variable frequency and constant amplitude, to a small electrode facing plasma [37]. The RF voltage induces an RF current circulating through the sheath and the plasma. In a capacitive arrangement a DC bias is built. As the RF frequency is increased the current is first independent of the frequency over a large range, is then amplified and later reduces almost to zero. This cut-off occurs because the electron plasma resonance of the crystal is reached. At frequencies approaching the plasma frequency, ω_{pe} , as for the plasma sheath resonance and the resonance probe, the region next to the central electrode, the plasma sheath, can be described in terms of positive permittivity (capacitive), while the complex plasma above has a negative permittivity (inductive). When in series resonance a peak in the current appears. The electron density in the dusty plasma can be obtained from the definition of electron plasma frequency, a cut-off unique to any geometry, for an analysis of the uncertainty see [38]. It is clear that only the free electrons participate in the resonances in our frequency range. In two component plasma physics the presence of ions does not modify much the electron plasma frequency, although the opposite is not true. In complex plasmas the lighter specie, electrons, has the same resonances with or without dust (see also the work on

the propagation of Langmuir waves in dusty plasmas). Any resistive element would not shift the resonance in frequency; it would only reduce the quality factor.

Alternatively the plasma resonances can be identified looking at the harmonics in the current induced by a fixed frequency voltage applied [39].

This method is particularly suitable when the high frequency time behaviour of the dust assembly, as for waves and pulses, is of interest. The Havnes parameter represents the ratio between the negative charge bound to the grains and the free electrons per unit volume, $H=n_D Z_D/n_e$. Apparently this diagnostic provides directly the denominator, even in the case of strongly interacting particle systems. This diagnostic is important for deciding the best removal techniques cause electrostatic techniques effectiveness and range depends on the electron density and radiofrequency extractors can work on resonant frequencies. See also table I

5) Visualisation and velocimeters

Measure the position and velocity of dust in plasma is essential in order to be able to evaluate the balance of forces on the particle, which may results in acceleration or in damped motion. In transients detached particles may arrive, or not, to equilibrium positions, where the density of dust builds up with the time. High thermal velocity particles are likely to escape from the plasma in all the direction (except the internal core) while slow particles are confined. However the measurement is not always straightforward because of the 3D nature of the space and velocity vector and the difficulty to have a directed light line in secluded places (where the dust is likely to settle).

In an experimental situation with directed motion, say along the magnetic field lines, because of directed ion drag, different techniques apply for different speed. For speed up to 1m/s the analysis of normal CCD camera frames, in sequence, is sufficient. However dust in Tokamaks may reach very high velocities, possibly even of the order of Km/s as deduced from measurement of the impact craters on probes [29]. Fast cameras up to 1200 frames per second are available, but with a limited field of view, for this reason it is difficult to catch the 'event'. Fast cameras need also strong luminosity but this is not a particular problem because fast particles are normally emitting. In systems optically semi-thin the position of stationary dust is detected fitting a Gaussian to the level of grey of the CCD pixels. The size can not be established thou; with visible light we can only measure particles $> \sim 50\mu\text{m}$ For a high density of dust it is not always easy to recognise the same particle from frame to frame analysis. For this case the laser flashing technique has been developed [40 -42]. In this technique the output of a laser can be modulated using a pulse sequence, for example providing 1ms of illumination with 9ms interval between each illumination, see for example fig. 3. With the CCD camera synchronised each video frame, $\sim 40\text{ms}$ in duration, captures three laser pulses. Individual particle can be identified in each frame and the spacing between the three spots allows a measurement of the particle velocity and acceleration.

The motion of the particles in tokamaks is 3D and this represents a strong limitation to the above techniques. This is particularly important for the motion in vicinity of curved surfaces, in the divertor, in turbulent flow. The illumination/recording should have access to the experimental space at two angles. A 3D visualisation diagnostic that simultaneously monitors the position and the velocity of particles is based on two over-imposed laser lights modulated in intensity in a complementary way [43]. The light of the two beams is scattered by the dust and collected, at an optimal angle by two selective cameras so that from the relative

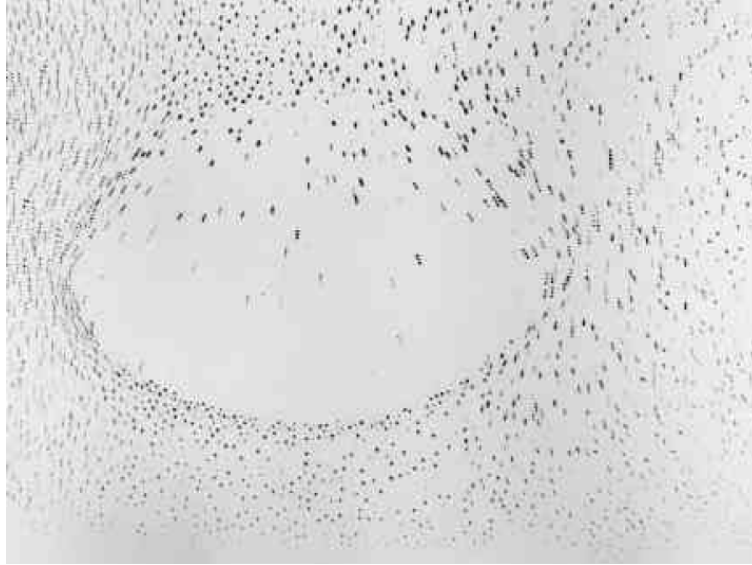


Fig. 3: A velocity field as visualized by the flashing laser light technique.

amount of laser radiation the depth of the particle can be resolved. The 3D velocity is derived by the length of the two traces left on the CCDs during the shutter opening time. A much simpler method of detecting 3D motion would require the mounting of a illumination source, together with one detector, on a port, to record the x,y plane. Synchronous acquisition from a detector in another port, ideally at 90° , would provide the plane y,z. It is then possible to establish numerically a correspondence between the 3 co-ordinates of each particle. In the same way it is possible to identify the 3D traces left during the exposure time.

Other detectors of high speed particles come from outer space dust detectors, which derive the dust particle velocities from measurement of the rise-times of the impact plasma signal [44]. Visualisation and measurement of the velocity have been used in tokamaks in ref. [45, 46], see also table I.

6) Temperature:

To establish the temperature of the dust is relevant because it controls the aggregation form and the chemical property of the dust. For example the amount of H, (D or Tr) stored in the dust depends on its temperature. The effective surface of the dust depends on its heath history. It is granular, cauliflower-shaped if it has always been cold and it is spherical if it has been near liquid phase. Other intermediate transitions, as amorphous carbon to graphite at $\sim 1000\text{K}$ have been observed. It is well known that molten Langmuir probes are typical accidents in SOL. The temperature of a grain in plasma is derived by equating the temperature dependent power loss to the energy rate input, [7, 47]. A dust particle can gain energy by the following mechanisms: ion bombardment, electron bombardment, ion-electron recombination, collisions with hot neutrals, molecular recombination at the surface, etc. A dust particle can lose energy by the following mechanisms: radiation loss, collisions with the cold neutrals, emission of neutrals from the dust particle (recycling). The equilibrium temperature derived is strictly dependent on the model of ion flow to the particle, directed, as in planer geometry, radial or orbital.

In an experiment particles fluorescent-coated have been added to plasma [48] Usually the temperature is detected experimentally by pyrometers [49]. See also table I

PART 3: REMOVAL OF DUST DURING THE PLASMA PHASE

Dust dispersed in the plasma phase is extremely mobile and can be concentrated in specific points where the removal from the vacuum vessel is most suitable. Several methods are reviewed in the follow and in the summary table II. We must however consider that even with frequent “removal from plasma” operations part of the dust will fall and accumulate in the divertor or will be dispersed on large surfaces at the bottom of the machine. Several techniques have been proposed including laser ablation and vacuum cleaning; all these techniques involve a system of surface scanning. This line of research is still at the very beginning and is outside the scope of the present review, for the mobilisation see, for example [50], for laser cleaning [51]. A convenient method to remove this dust is re-levitation to bring the dust back in plasma in which it can be manipulated.

Table II. Proposed removal technique with feasibility in principle in the ITER environment

Removal technique\ feasibility in ITER	Feasibility	Technical requirements	Compatibility with radiation, fields and temperature	Need more R&D
DC positive biasing	Certainly during glow discharges. Possibly also during long shots. Efficiency is reduced by the pressure.	Better located in the lower part of the vessel. It should not work against gravity	Along the B field lines if high fields are present.	Never been tested on large systems. Theory of the sheath in front of positive electrodes. Effect of the shape.
RF driven manipulator	Certainly during glow discharges. Possibly also during long shots. Efficiency is reduced by the pressure. It may have a longer range than the DC case	Better located in the lower part of the vessel. It should not work against gravity. It needs adjustable frequency power supply.	Along the B field lines if high fields are present.	Never been tested on large systems. Theory of the RF heavily loaded sheath. Effect of the shape.
Cold finger	This technique is independent of pressure, however it is unlikely to have a sufficient control of all temperatures of the vessel to plan thermophoresis	At high pressure the power required to sustain a temperature gradient is higher	Scarse. Thermophoresis may be already a dominant force without applying the cold finger!	Technological control of the temperature of the surfaces

1) DC positive biasing

Dust can be removed from plasma by DC positive biasing of small areas, see ref. [52, 53]. The area should be small to allow its potential to be well above plasma potential (about one ionisation energy) without dragging the plasma potential more and more positive. Not to perturb the plasma features the electron current collected by the positively biased extractor must be small with respect to the total electron current leaving the plasma, which coincide with the total flux of the ions. The electron temperature, T_e , and density, n_e , would not change if:

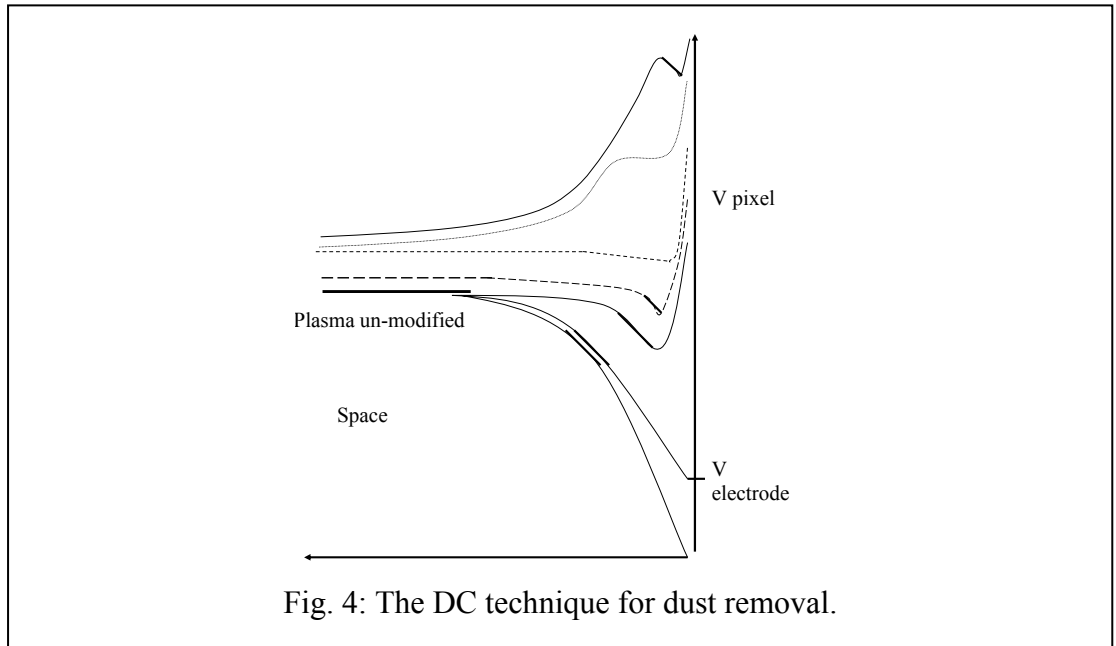
$$\frac{A_x}{A_T} \ll e^{-1/2} \sqrt{\frac{2\pi m}{M}} \quad 3$$

with A_x and A_T the areas of the extractor and of the vessel and m , M , the mass of the electrons and of the ions respectively. For H_2 this ratio is about 2.5%. For Argon $\sim 0.5\%$. A more stringent criterion, with respect to the above, can be obtained to keep unaltered the plasma potential and the capacity of the sheath.

The sheath above a positively biased pixel is a complex phenomenon, see for example fig. 4. A good insight can be given by the comparison with the DC discharges at the anode, as in Langmuir theory [54]. A plasma sack forms when the electron current, I_e , tends to overcome the electron random flux, i. e.:

$$I_e > \frac{An_0 \bar{C}_e}{4} \quad 4$$

where C_e is the thermal velocity. The boundary of the localised glow is a double layer sheath with an inner positive-ion space charge and an outer electronic space charge. The extended negative pre-sheath attracts dust far away in the plasma. A qualitative schematic of the voltages in front of a biased pixel is shown in figure 5. In analogy with the positive pre-sheath, where the electrons are the rejected specie, the potential of which is $\sim kT_e/L$, with L the plasma dimension, we suppose a



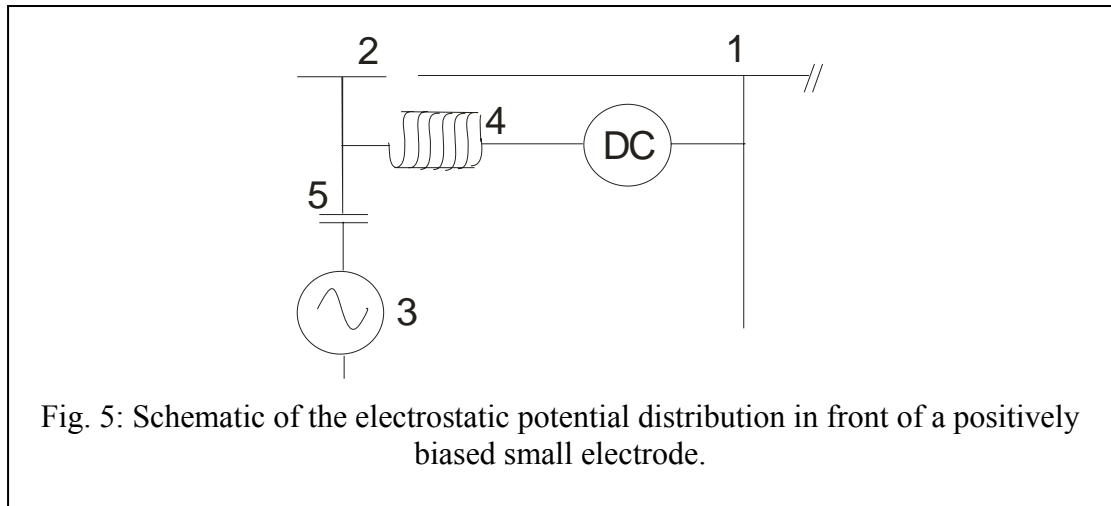


Fig. 5: Schematic of the electrostatic potential distribution in front of a positively biased small electrode.

negative pre-sheath when ions are rejected, of the order of kT_i/L . This small E field, $\sim 0.025\text{eV}$, is sufficient to give detectable force to multi-charged particles, $Q \sim 10^4e$.

This manipulator addresses dust of any negative charge. Positively charged dust is not confined and escapes from plasma (it may be found in tokamaks due to secondary emission due to thermionic emission [55], radiation, for carbon the photoelectric threshold is 4.8eV , or nuclear decay of the tritium). The range of action of these manipulators has not been determined yet. The parameters involved would be: electron mean free path (m.f.p.), which depends on the basic neutral pressure, charging conditions and other. This removal technique is possible in the glow discharge of Tokamaks because the base pressure is low cause the large volumes. At 0.1Pa , the mean free path for momentum transfer of the electrons is about 0.5m . The range of influence of the collector should extend on several m.f.p..

2) RF driven manipulator

When RF is applied to a small electrode, grounded in DC through an inductance as in fig. 5, a large electron current flows to the electrode in the part of the RF cycle when the electrode is positive w.r.t. plasma [56, 57] and fig. 6. In average though, the potential of the plasma in front of the electrode remains positive. Effects on dust particles in plasma are much similar to the DC case described above.

The dust is collected from far away, but do not fall on the electrode unless a small positive DC is applied ($2\text{-}3\text{V}$). By careful matching amplitude and phase of the

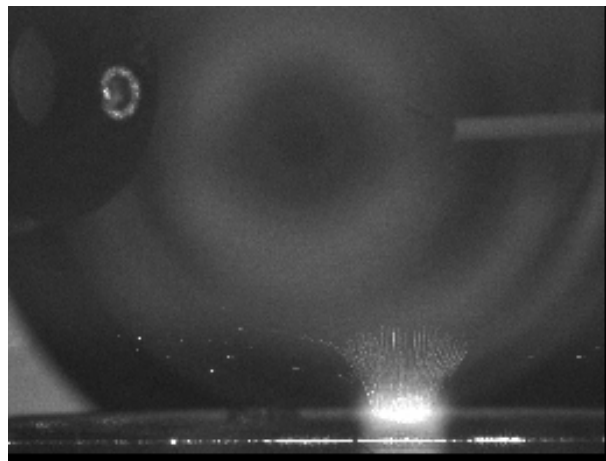


Fig. 6: Connection for the RF manipulator in attractive mode.

radiofrequency it is possible to collect, store and re-inject dust in a versatile way. In a certain range of parameters nano-sized dust (fog) can be aggregated to form larger clusters, up to millimeter size. Another advantage of this method with respect to the DC collectors is that the flow of the ions out of the plasma is not modified. Matching frequency of the RF source to the plasma-sheath resonance [58], or to the dusty plasma sheath resonance, the effect is strongly amplified and dust is collected (or rejected) from far away. The collector(s) can be located in any surface exposed to plasma and for small and medium size dust the position is independent from the directions of the system, including gravity (for particles above 1 μ m diameter it is convenient to mount the manipulator in the lower part of the system). If more than one type of plasma and complex plasma are present at the same time in the reactor (to give an example: a two component plasma in a certain region, a nano-particle dispersed plasma ‘fog plasma’ in another region near sputtered surfaces and a dense complex plasma of micron size particles over the lower surfaces) it is possible to remove in sequence different types of dust.

3) Thermophoresis

Thermophoresis, is the force due to molecular impact on the dust particle in a temperature gradient. It may be unrealistic to base the dust removal in tokamaks on thermophoresis because in fusion devices it may not be easy to have a complete control of the temperature of the walls. However it is important to include this force in the review because thermophoresis may be present, even if unwanted, and because, being independent on the dust charge, it can be used in laboratory experiments and small devices to characterise other forces, as ion drag and electrostatic. There are two distinct regimes: continuous regime for a diameter of the particle much larger than the mean free path: $d_p > \lambda$ (Knudsen number > 1) and free molecular regime for $d_p < \lambda$ ($Kn < 1$). In the continuous regimes, to give an example for particle $\sim 1\mu$ m in atmospherical pressure, the thermal force on the particle is:

$$F_{th} = \frac{-9\pi\mu^2 d_p H \nabla T}{2\rho_g T}$$

with:

$$H \cong \left(\frac{1}{1+3K_n} \right) \left(\frac{k_a/k_p + 2.2K_n}{1+2k_a/k_n + 4.4K_n} \right)$$

μ is the dynamical viscosity and k_a , k_p are the thermal conductivity of gas and particle, see also [59, 60]. In free molecular regime, typical of plasma and glow discharges, we have:

$$F_{th} = \frac{-p\lambda d_p^2 \nabla T}{T}$$

where p is the pressure. This force is in fact independent of pressure and can be re-written as:

$$F_{th} = -0.83 \frac{k_B d_p^2}{\sigma} \nabla T$$

with σ the atomic cross section of the gas, see table III, and k_B is the Boltzman constant. However in high pressure more power is required to maintain the

temperature gradient.

Unlikely the other forces, the thermophoresis in the free molecular regime is independent from the particle charging and material and therefore it can be applied also to dust suspended in gas. Experiments with a “cold finger” in small laboratory plasmas have shown an effective collection of dust [61]. Thermophoresis applied in Tokamak has been discussed in [62].

Thermophoresis of spherical and non spherical particles is reviewed in [63].

Table III The dependence of the thermophoresis on the gas. The force on the particle is calculated for three typical gases of glow discharge

Gas	He	Ne	Ar
σ (10^{-20}m^2)	15	21	42
$F_{\text{thermophoresis}}$ (10^{-14}N) (for a gradient $117\text{K}^0/\text{m}$ and diameter $=3.38\mu\text{m}$)	10.2	7.31	3.66

3) UV light and radiation pressure

Photoemission of electrons from dust grains may occur in the presence of a flux of ultraviolet (UV) photons with energy larger than the work function of the grain material. see ref. [64]. In this case, the charge of the particle is reduced and the electrostatic forces may not be sufficient to compensate for the gravity. Dust of dimension comparable or larger than microns is so induced to deposit in places convenient for the removal. UV light relevant work can be found in [65, 66]

Radiation pressure is independent of the charge, [67], so it can be used in a variety of experiments to stimulate particle motion and/or shift equilibrium positions. The quality of the dust surface is important because different amounts of momentum are transferred when photons are absorbed diffusively or reflectively.. For the particular application of removal of dust suspended in tokamaks, the radiation pressure removal method is probably difficult. With small ports the laser light is in general divergent. Convergent or parallel light can only scan small volumes.

CONCLUSION

Dusty plasma is an inherently interdisciplinary subject, which has developed, in the last few years, a large patrimony of fundamental understanding. Elaborating this knowledge to provide an answer the technological needs is not an easy task, either towards low temperature plasma processing or towards fusion technology. These two applications of plasma physics are somehow independent, even the scientific language used has become specialised. This review, notwithstanding its limits, tries to bridge these differences.

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APPENDIX

Example of work still to develop

Calculation of the charge in:

Dust in strong electric field: $E \cdot \lambda_D > V_{\text{floating}}$

Dust under radiation

Dust in magnetic field

Dust in e-i beam

Dust emitting electrons

Influence of materials

Influence of shapes and equivalent area

Time domain:

Charging time

Permanence of the charge

Charge fluctuations

Re-levitation of particle

under strong electric field

by laser

Neutral drag (gas puffs)

Forces and transport

on the single particle

among particles

Growth

Nucleation

Aggregation

Deposition

Detachment from walls

Sputtering

As debris or flakes

Co-existence dust-plasma

Range of penetration in the scrape-off/divertor

Melting and vaporization

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