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In situ dust detection in fusion devices

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Abstract
Diagnostics for monitoring dust in tokamaks during plasma discharges, both established and currently being developed, are discussed with a focus on the range of dust parameters they can detect. Visible imaging can currently be used for dust particles bigger than a few μm and velocities below $1\,\mathrm{km\,s^{-1}}$. The dust impact ionization phenomenon can be used for the detection of particles with velocities above a few $\mathrm{km\,s^{-1}}$. Laser light scattering gives an insight into the amount of sub-micron dust. Aerogels, light porous materials, allow capturing of dust particles without destroying them and determining their velocity. Other methods include the microbalance technique and electrostatic dust detectors. A recent suggestion to use the effects of dust on collective scattering for diagnostic purposes is also discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The importance of the issues of dust production and dynamics in tokamaks has been recognized for a decade now [1–4] and currently the main challenge is the diagnostic of dust. While the postdischarge methods, such as analysis of the particles and debris collected in tokamaks at the end of experimental campaigns [2, 3], have been long established, the detection of dust present in the plasma during discharges is an open problem [5, 6].

The main parameters of interest, apart from the particle material, are dust velocity, size and number density. To understand the requirements for dust diagnostics it is essential to establish the expected ranges of these parameters. Due to the uncertainties in the present estimates of the dust parameters it is important that diagnostics cover the maximum possible range of these parameters in order to not overlook some dust populations. In this paper we discuss established diagnostics as well as those currently being developed, paying particular attention to their limitations.

Visible imaging, discussed in section 2, allows one to estimate the velocity of individual dust particles from the recorded trajectories. The observed velocities are of the order of $0.1\,\mathrm{km\,s^{-1}}$ and the highest value reported is $0.5\,\mathrm{km\,s^{-1}}$, for a bright dust grain with a diameter of several micrometers. Due to limitations of the diagnostics, it cannot be excluded that smaller, undetectable particles might be accelerated to higher velocities.

Some evidence of micrometer-size particles impinging on solid targets at velocities of several $\mathrm{km\,s^{-1}}$ has been recently observed in FTU during plasma discharges. If these observations are confirmed in other machines, in plasma conditions relevant for fusion reactors, the fast dust population should be carefully monitored, due to the potential hazards of wall erosion. Section 5 discusses dust impact ionization phenomena which can be used as a diagnostic for such fast particles.

Laser light scattering can be used to evaluate particle size as well as the number density. The smallest detectable dust size is limited to a few percent of the laser wavelength, due to the sharp decrease of the scattering cross section for particle diameters much lower than the laser wavelength. The maximum detectable particle size is limited to a few laser wavelengths, due to the saturation of the detectors of the scattered light. For present diagnostics, which are based on Thomson scattering (TS) systems with laser wavelength of about $1\,\mu\mathrm{m}$, the range of the detectable dust sizes is therefore from a few tens of nanometers to a few micrometers. As discussed in section 3, careful modeling of the scattering process as well as of the laser–dust interactions is necessary to extract information on the particle sizes.

Estimates of the number density can also be obtained from the laser scattering data, but not as a real time measurement as it requires several laser pulses in several shots. Ideally, one would like to measure the particle density and evolution everywhere in the scrape-off layer (SOL) in order to understand possible sources and sinks. A new kind of diagnostics, based on the electromagnetic scattering in the millimeter-wave range, has recently been proposed to provide information on the time evolution of the dust number density, see section 4.

Dust collection provides information on dust size and amount; the latter, however, does not necessarily reflect the amount of dust present in the plasma during the discharge. The analysis of deposits in tokamaks showed a large spread of dust sizes, from sub-micrometer up to $100\,\mu\mathrm{m}$, with mean value of about $1\,\mu\mathrm{m}$ [3]. While some estimates for the number density of micrometer dust are available, knowledge about densities of nanoparticles, which could also exist as localized clouds, is limited [2, 7].

A new method for dust collection, discussed in section 6, is based on the use of aerogel, a highly porous, very low density material. Aerogel collectors can capture dust grains without destroying them. Moreover, analysis of the tracks of captured particles allows one to evaluate the dust velocity, even in the high velocity range (several $\mathrm{km\,s^{-1}}$).

Other dust diagnostic systems, namely microbalance technique, electrostatic and acoustic detectors are briefly discussed in section 7.

2. Visible imaging

Imaging with cameras is widely used for dust characterization in fusion devices [8–12]. The technique allows recording of trajectories of individual dust particles and estimating of the particle velocities; however, particle size is difficult to determine. Standard frame rate cameras (60 frames $\mathrm{s^{-1}}$) generally exhibit a poor contrast ratio for objects moving against the background and can therefore detect only large particles (tens of micrometers in diameter or larger). Fast-framing or gated cameras can resolve smaller, faster moving particles. Dust is usually observed in full light or with near IR filters [10, 11], but occasional observations with spectral line filters such as D_α and CIII are also made. A single camera view allows estimating of

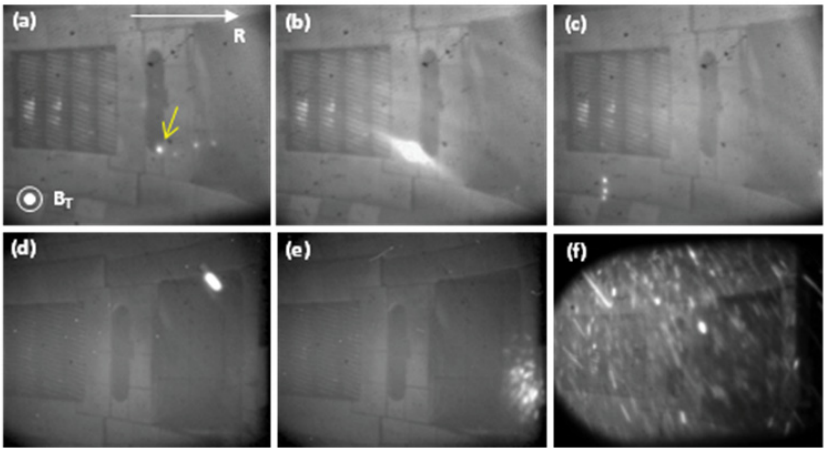

Figure 1. Dust in DIII-D (fast camera, tangential view of the outboard SOL): dust moving in the SOL toward the core (*a*), developing a large ablation cloud (*b*), splitting in three pieces (*c*), fast ($500\,\mathrm{m\,s^{-1}}$) dust particle (*d*), colliding with the wall and producing debris (*e*) and dust produced by a disruption (*f*).

dust particle velocities projected on a plane perpendicular to the line of view of the camera. This is inevitably a low-bound estimate, since the parallel velocity component cannot be resolved. Use of multiple cameras with intersecting views allows unfolding particle trajectories in full 3D and estimating of the actual velocities. However, implementing intersecting camera views in a conventional tokamak is often non-trivial due to a lack of access. An advanced fast camera setup implemented on NSTX [10] takes advantage of the open geometry of a low aspect ratio tokamak. Intersecting views of the outboard SOL and lower divertor are available, and 3D trajectory reconstruction is performed with an estimated accuracy of ± 4 cm.

Dust observation rates depend on the PFC material and design, wall conditioning, discharge parameters, etc. For example, in DIII-D during 'normal operations', i.e. when the vacuum vessel walls are well conditioned and there are no major disruptions, dust observation rates are low. Standard cameras register only isolated dust events in their field of view, while a fast camera (operated at up to 26 000 frames $\mathrm{s^{-1}}$) [12] typically observes between 10 and 100 events per discharge. Individual particles have been observed to move at velocities of up to $500\,\mathrm{m\,s^{-1}}$. The breakup of larger particles into pieces is also observed. A sequence of frames in figures 1(*a*)–(*c*) (taken by the fast camera in full light, at 2000 frames $\mathrm{s^{-1}}$ with 497 μs exposure per frame) shows a comparatively large and slow (probably tens of micrometers in size and $10\,\mathrm{m\,s^{-1}}$ in velocity) dust particle marked by an arrow in (*a*) that first becomes visible in the outboard SOL, moves towards the plasma core (*b*), then changes direction and breaks into three smaller particles (*c*). Collisions of dust particles with vessel walls are sometimes observed. Figure 1 shows a dust particle traveling at $500\,\mathrm{m\,s^{-1}}$ (*d*) that hits the outboard wall (out of the field of view) and results in ejection of debris (*e*). Disruptions often generate significant amounts of dust which is directly observed by the fast-framing camera. An image of dust produced by a disruption is shown in figure 1(*f*). A single disruption produces up to $\sim$1000 dust particles within the camera view, corresponding to $\sim$10 000 particles for the whole vacuum vessel.

In principle, if chemical composition and local plasma parameters at the location of a dust particle are known, one can relate the intensity of thermal radiation from a particle to the particle size [13]. If an absolute *in situ* calibration of the camera sensitivity is available, it may be possible to determine the particle size from the intensity of a recorded image; however, in practice this task is extremely complicated. In the regions where the plasma density and temperature are sufficiently high to cause significant ablation of a particle surface, radiation from the ablation cloud around a particle can contribute significantly to or even dominate the detected radiation. This is illustrated in figure 1(*b*) where a large particle clearly develops an ablation cloud appearing as a bright halo elongated along the magnetic field lines. An alternative approach for determination of particle size from camera data involves comparison of particle lifetime in the plasma with a theoretical ablation rate of a carbon sphere [13]. This method has been recently applied in DIII-D. Observed particle sizes between 6 μm and 1 mm and inverse correlation between the particle size and velocity have been inferred [13]. The latter observation underscores the difficulty in detecting small dust with cameras: not only are the particles small requiring high sensitivity but they are also fast, requiring higher contrast ratio with respect to the background.

Injections of pre-characterized dust from a known location can be used to calibrate diagnostic measurements and benchmark modeling of dust dynamics and transport. Migration of carbon dust has been studied in DIII-D by the introduction of micrometer-size (6 μm median diameter) graphite dust in the lower divertor [14]. Following a brief exposure (0.1 s) at the outer strike point, part of the dust was injected into the plasma. The fast-framing camera observed large amounts of injected dust in the outboard SOL. An injection of diamond dust of finely calibrated size between 2 and 4 μm was recently performed. Dust from the injection was observed by the fast camera, but required digital background subtraction to be resolved [11]. Therefore, it was experimentally demonstrated that 4 μm dust is about the smallest that can be resolved by the fast camera in the existing setup at DIII-D.

3. Laser light scattering

TS diagnostics have been used in tokamaks to achieve estimates of the dust size and number density during normal plasma discharges as well as after disruptions.

TS diagnostics are widely used in tokamaks to measure the electron temperature and the plasma density [15]. TS systems often feature detection channels at the laser wavelength that are used for calibration by Rayleigh scattering. While not useful for TS, these channels may be used for dust detection based on the elastic scattering of the laser beam by dust particles. Particle size can be estimated (from the intensity of the scattered light) with proper modeling of the laser–dust elastic cross section, which requires assumptions on the geometrical and optical properties of the dust grains. The average particle number density can be calculated as the total number of scattering events, divided by the product of the scattering volume and the total number of laser pulses considered.

Dust particles produced upon disruption were first detected in the JIPPT-IIU tokamak and their size was estimated assuming the spherical shape of the grain and elastic scattering with a geometrical cross section [16]. The dust radius for a single particle detected by TS was found to be in the range 0.4–1.0 μm, but the number of dust scattering events registered was not sufficient to deduce the dust size distribution.

For particles with size less than 0.1 μm the Rayleigh approximation can be used. The Rayleigh scattering cross section is proportional to the particle radius to the sixth power, so the diagnostic becomes very insensitive to particles smaller than a few tens of nanometers. Assuming the Rayleigh regime of laser light scattering (RLS), and perfectly conducting dust spheres, the distribution of the sizes of dust particles was measured in the SOL of DIII-D during normal plasma discharges [17]. A particle density of $\sim 6 \times 10^3\,\mathrm{m}^{-3}$ and average dust radius of ~80–90 nm were estimated.

RLS was also used to evaluate the dust size with the TS diagnostic installed on the FTU tokamak [18]. As there were no spectrometers able to see the SOL, the measurements have been carried out after disruptions (there is no evidence of elastic scattering by dust in the main plasma during normal operation). Particles with average radius of the order of 50 nm and average density $10^7\,\mathrm{m}^{-3}$ have been detected. The size distribution of the particles seems to follow a power law $\sigma^{-\lambda}$, where σ is the geometrical cross section of the grains and $\lambda \sim 2$.

For larger particles the generalized Mie scattering theory should be used, taking into account spheroidal shape parameters and off-axis Gaussian-beam illumination [19]. It should be stressed that estimations of particle size by laser scattering are affected by arbitrary assumptions on the geometry of the grains, on their illumination by the laser beam as well as on their (complex) refractive index. Moreover, the simple scattering picture is complicated by nonlinear laser–dust interactions which are expected to occur. The scattering cross section for TS is indeed so small (the total cross section is about $6.6 \times 10^{-29}\,\mathrm{m}^{-2}$) that Q-switched lasers at optical wavelengths are generally used (Nd : YAG or Ruby lasers are the most common laser sources). The total power of these lasers is of the order of a few joules in about 10 ns. As they are generally focused into the plasma, an intensity in the range from $10\,\mathrm{kJ\,m}^{-2}$ up to a few $\mathrm{MJ\,m}^{-2}$ is easily achieved. This energy density delivered in 10 ns might be enough to vaporize dust particles with a size of less than few micrometers. Generation of plasma in the vapor cloud is also possible. Therefore, scattering and absorption by vapor and plasma cloud should be taken into account in evaluating the particle size. A signature of the presence of a dense vapor/plasma cloud should be the occurrence of a light signal, due to neutral gas emission lines, correlated in time with the elastic scattering signal. Broad band emission, well correlated with the light scattered at the laser wavelength, was indeed often observed both in the FTU and JIPPT-IIU tokamaks after disruptions. However, no evidence of emission at different wavelengths correlated in time with the elastic scattering signal was found in DIII-D. The scattering region in DIII-D was located in the SOL, where the cross section is much larger than in the main plasma column where the beam is focused and where the dust scattering was observed in JIPPT-IIU and FTU. Hence the laser beam intensity in the scattering volume is expected to be lower for DIII-D than JIPPT-IIU and FTU, and nonlinear effects are less important.

Neglecting scattering and absorption by the vapor/plasma cloud, improved estimates of particle size were performed, based on DIII-D scattering data, taking into account the effect of thermal evaporation (the evolution of the dust radius with time during the laser pulse) and Mie theory for spherical particles [20]. As a result, the average dust radius was found to be a factor of two larger compared with the previous estimate. The distribution of the particle radii r was fitted by a power law $r^{-\gamma}$ with $\gamma \sim 2.8$ (thus large radius particles dominate the mass inventory). Preliminary results of a similar analysis carried out on FTU data suggest that the simple RLS theory underestimates the particle radii by a factor 2–5. It is worth noting that the inventory of the dust collected from the chamber wall in DIII-D showed a mean particle radius in the range 0.32–0.94 μm. Therefore, an extension of the range of the measurable particle radii, limited now to about 1 μm by the scattered signal saturation, and improvement of the statistics (e.g. by increasing the scattering volume) seem necessary to obtain information on the tail of the particle distribution corresponding to large radii.

In conclusion, laser light scattering is a promising diagnostic for evaluation of the particle size and number density. However, large uncertainties on the refractive index, geometrical parameters and nonlinear laser–dust interactions, as well as a lack of statistics for scattering events by micrometer size dust do not allow reliable and precise measurements of the dust distribution. Dedicated diagnostics systems, e.g. utilizing sources at different wavelengths and lines of sight at different scattering angles, as well as more accurate modeling of the laser–dust interactions should be developed. In this vein, the analysis of the broad band signal, correlated with elastic scattering when a dust particle is illuminated by an intense laser beam, might provide useful information on the dust size and composition.

4. Collective scattering

The evaluation of the dust density by laser light scattering, as described above, cannot be considered as a real time measurement. It relies indeed on statistics of elastic scattering events, which requires several laser pulses in several shots. A new diagnostic, also based on electromagnetic radiation scattering, has recently been proposed to measure dust density evolution during plasma discharge. Dust grains can modify the collective plasma scattering via transition scattering [21, 22], i.e. by coherent scattering from electrons in the Debye shielding cloud of radius λ_D. The transition scattering cross section increases with increasing wavelength λ and the limiting value, for $\lambda \gg \lambda_D$, is $\sigma_0 Z_d^2$, where σ_0 is the TS cross section and Z_d is the grain charge number. For realistic dust density and dust sizes expected in tokamaks, the transition scattering should not significantly change the radiation scattered by the plasma electrons without dust (i.e. $n_d Z_d^2 \ll n_e$, where n_d is the dust density), though it could, in principle, be used to evaluate the dust charge.

The presence of the dust grains also strongly modifies the spectra of the radiation scattered from the plasma fluctuations [23]. For a frequency difference $\Delta\omega$ of the injected and scattered waves much larger than the ion Doppler shift $|\Delta \boldsymbol{k}|v_{th,i}$ ($\Delta \boldsymbol{k}$ is the difference of the wave vectors of the injected and scattered waves and $v_{th,i}$ is the ion thermal velocity) the intensity of the scattered waves increases in the presence of dust grains by the factor $f = x^{-3/2}\exp^x \nu_{coll}/\Delta\omega$. Here $x = (\Delta\omega/|\Delta \boldsymbol{k}|v_{th,i})^2$ and $\nu_{coll} \approx \pi a^2 n_d v_{th,i}$ is the collision frequency of ions with dust of radius a.

Collective Thomson scattering (CTS), based on the scattering of electromagnetic waves off microscopic fluctuations, driven by ion motion, has been successfully employed to measure the ion temperature [24] and the fast ion population [25] in tokamaks. The powerful (0.1 MW) probe beams in the millimeter-wave range used for CTS, could also be used to measure the ion–dust collision frequency (and to deduce the dust density). The frequency spectra of the intensity of the waves scattered off plasma fluctuations in the SOL must be compared with the theoretical predictions for the spectra expected without dust, to obtain the amplification factor and hence the ion–dust collision frequency from the above equation for f.

In conclusion, evaluation of the dust density based on scattering of electromagnetic radiation off plasma fluctuations in the SOL is, in principle, feasible. However, it requires a proper modeling of the scattering process with and without dust, and reliable measurements of the SOL plasma parameters.

5. Dust impact ionization phenomena

Recent measurements have shown some evidence that micrometer-sized particles may be accelerated to very high velocities—several km s^{-1} [26, 27]. If particles with such velocities impact the wall, the ejecta far exceed the projectile masses. This provides fresh particles as well as the release of neutral gas and plasma [28] and hence, even if such particles are rare, their detection is important.

For almost all materials the hypervelocity regime (when the speed of an impact exceeds the speed of the compression waves both in the target and in the projectile) has been reached when the impact speed exceeds a few km s^{-1}; it is therefore common to consider velocities

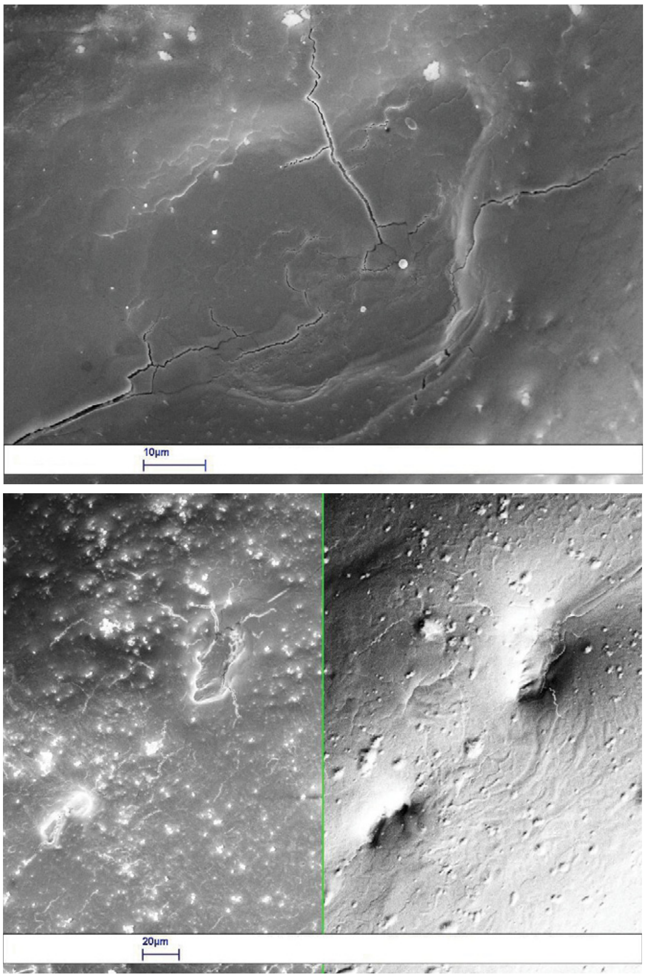

Figure 2. Electron microscope analysis of the surface of the probe used for hypervelocity dust detection in the FTU tokamak [31, 32]. The indicated scale is 10 μm for the upper figure and 20 μm for the lower figure. The top image and the bottom left image were taken by a secondary electron detector; the bottom right image was taken by a electron back scattered (EBS) detector.

above 2–3 km s^{-1} as hypervelocity impacts [29]. The resulting pressure can reach 1 TPa and the temperature can be sufficient to cause vaporization and ionization of the materials.

The impact ionization phenomena can be used as diagnostics of such fast particles. It was originally proposed by Friichtenicht [30] in the 1960s and is presently widely employed in space research (see e.g. [31]). Such dust detectors generally make use of the phenomenon either by measuring the current created on the target surface or by time-of-flight mass spectrometric analysis of the resulting ions ([31, 32] and references therein). Another way to obtain information on the projectile parameters is to study the typical footprints of the hypervelocity impacts—the craters on the target surface [29, 30].

The charge released upon such impacts depends on target material and projectile material, velocity and mass. Laboratory studies show, e.g. [29], that a charge in the range $\sim 10^{11}$–$10^{13}e$ (where e is elementary charge) can be released upon an impact of an iron spherical particle of a few micrometer radius on a molybdenum surface at velocities from a few to tens km s^{-1}. For an order-of-magnitude estimate of the corresponding current we can use the typical charge collection time, 10–100 μs, reported for dust detectors which operate in vacuum (see e.g. [31] and figure 3 and table 3 therein). This yields a current of the order of 10 mA which can be distinguished from the background of the ion saturation current near the chamber walls where the plasma density is low. Such measurements have been reported in the FTU tokamak where the rare and extreme probe signal spikes have been interpreted as dust impact ionization by micrometer size iron particles impinging on the probe surface with velocity of the order of 10 km s^{-1} [27].

The dimensions of craters on the target surface produced by dust impact are functions of the projectile parameters and empirical formulae for different material are available, see e.g. [33]. Hence, quantitative analysis of the number and size of craters on the surface of targets exposed to plasma for a given time may yield number density, velocity and size of hypervelocity dust particles. The crucial issue for tokamak environments is to distinguish such impact craters from commonly observed unipolar arcs [34].

According to the first observations [27, 26], there is a difference in the topography. As seen from figure 2 the configuration of the craters found on the probe tip used in the above mentioned measurements is very smooth, i.e. the rough rims from ejected molten metal typical for unipolar spots are missing. Plasma etching could have affected the craters, erasing such features. However, this seems not to be the case, because it is still possible to see the roughness from the machining of the probe surface (see figure 3 of [26]). The small cracks observed also suggest an origin due to impacts rather than arcs—since the surface damage by the latter is mainly due to heating by the arc current which causes melting of the material. Moreover, in tokamaks, the arc hops from one spot to another, causing scratches typically of several millimeters length [4]. Such scratches were never found on the probe surfaces used in the experiment.

It is worth noting that light emission associated with dust impact ionization [35] might provide further information on the dynamics of the impacts.

6. Aerogel samples for dust capture

A primary candidate for the collection of dust particles in the SOL plasma is an aerogel target [36, 37]. This highly porous, very low density material, in principle, allows capture of even hypervelocity particles without destroying them (figure 3), and is already widely employed to study cosmic dust [38, 39]. The use of aerogels might provide information on the velocity and size distribution as well as the composition of dust particles in tokamaks.

Silica (SiO_2) aerogels appear most suitable for tokamak applications. The aerogel is composed of clusters of 2–5 nm solid silica spheres with up to 95% empty space, an average pore size is 2–50 nm and mass density 0.1 g cm^{-3}. It has low thermal conductivity, refractive index and sound speed in addition to its exceptional ability to capture fast moving dust. Silica aerogels are made by high temperature and pressure-critical-point drying of a gel composed of colloidal silica structural units filled with solvents.

Studies of the compatibility of pure silica aerogels with plasma conditions near the walls and tokamak vacuum requirements have been carried out. It has been found that sample outgassed species are dominated by vapor H_2O with traces of N_2 and CO, O_2 and CO_2. Samples can withstand 48 h of heating to above 300 °C. They are easily pumped; with a sample of a few cm^3 volume introduced into a 70 L chamber and with a pumping speed of 60 L s^{-1}, vacuum of 10^{-6} mB can be reached in 6 h and 10^{-7} mB in less than 24 h—without a noticeable difference in outgassing with and without the sample.

Erosion of silica aerogel samples does not appear to present a serious problem for typical SOL conditions. Sputtering yields for SiO_2 by deuterium charge exchange neutrals are not

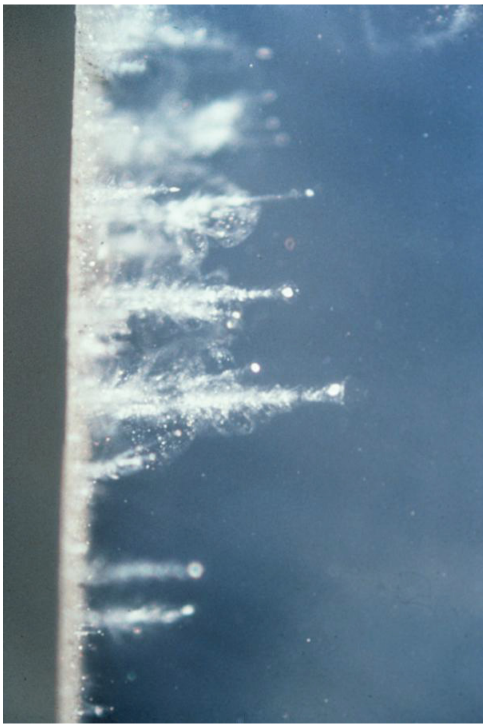

Figure 3. Particle tracks in aerogel. From http://stardust.jpl.nasa.gov/tech/aerogel.html.

available, but for an estimate we can use yields for D on SiO [40]. Let us assume the sample is exposed to deuterium neutrals, with a number density of $10^{12}\,\mathrm{cm}^{-3}$, and a temperature of 30 eV, that would correspond to a deuterium flux $5 \times 10^{18}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The sputtering yield averaged over a Maxwell distribution with the above quoted ion temperature is $\sim 6 \times 10^{-3}$ atom/per neutral which gives a flux of SiO_2 of $3 \times 10^{16}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This is an upper limit estimate since closer to the wall the plasma density and ion temperature are much lower—hence the SiO_2 flux is orders of magnitude smaller. In fact near the wall sputtering might not take place at all as for light ions incident on heavy materials the threshold energy for Si is above 12 eV [4]. Moreover, [41] reported on experiments after siliconization of the vessel, yielding typical silicon fluxes from the inner wall of 10^{15} atoms $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Let us evaluate the volume of the aerogel needed to capture fast metal particles. Using the simple model of grain stopping once it has intercepted its own mass worth of aerogel we find a track length of $l \sim 100\,\mu\mathrm{m}$. With the dust flux $\sim 3 \times 10^2\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$ [27] and a typical duration of the experiment of 1 s, a collection volume of $1\,\mathrm{cm}^2 \times 1\,\mathrm{cm}$ should be satisfactory.

Issues about the extraction and analysis of captured dust are discussed in detail in [42, 43]. Note that in case better contrast for electron microscope analysis is required to distinguish between aerogel background and captured particles, there is a range of different material aerogels available.

The first experiments with silica aerogels have been performed recently in the medium size HT-7 tokamak with graphite limiter in Hefei, China [44]. The aerogel sample of $40 \times 28 \times 28\,\mathrm{mm}^3$ extended radially into the SOL and has been exposed to 10 plasma discharges, each of 1 s duration. The experiment was performed with a plasma current of 130 kA, magnetic field 1.8 T and line averaged plasma density $10^{19}\,\mathrm{m}^{-3}$. About 800 traces with entry diameters from 10 μm to 0.5 mm and depths up to a few mm have been detected in the sample. Presently the data are undergoing detailed analysis; x-ray tomography of the sample to a resolution of 5 μm and electron microscope analysis of particles captured in the aerogel.

Currently aerogel samples are also being installed in the FTU tokamak and reversed pinch experiment 'EXTRAP T2R'.

7. Other diagnostics

An electrostatic detector has been developed for dust detection on remote surfaces in air and vacuum environments [45–47]. The detector consists of a fine grid biased to a few tens of volts and counting electronics which register the current pulse resulting from a temporary short circuit due to an impinging particle. The sensitivity of the grid detector is about 40 ng cm^{-2}/count and though not sufficient for contemporary machines is adequate for ITER [46].

Another dust diagnostic proposed for next-step fusion devices is the microbalance technique [48, 49]. It utilizes the capacitive diaphragm gauge—a gravimetric device which can measure the cumulative weight of dust, flakes or film growth on the surface of the diaphragm (by determining the change in the capacitance caused by its deflection relative to a fixed plate.) A prototype device with a sensitivity of 500 μg cm^{-2} controlled by remote electronics has been developed and tested in the laboratory [49].

Acoustic sensors for dust detection have been developed for space dust experiments, see, for example, [50] and references therein. The feasibility of their application for tokamak environments has not yet been investigated.

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References

[1] Tsytovich V N and Winter J 1998 *Phys.—Usp.* **41** 815
[2] Winter J 1998 *Plasma Phys. Control. Fusion* **40** 1201
[3] Carmack W 1999 *J. Rep.* INEEL/EXT-99-00095
[4] Federici G *et al* 2001 *Nucl. Fusion* **41** 1967
[5] Wang Z *et al* 2008 *Proc. 2007 ICTP Summer College on Plasma Physics-New Aspects of Plasma Physics* ed P K Shukla, L Stenflo and B Eliasson *Physics of Dust in Magnetic Fusion Devices* (Singapore: World Scientific) p 391–475
[6] Rudakov D *et al* 2008 Dust measurements in tokamaks *Rev. Sci. Instrum.* at press
[7] Hong S *et al* 2007 *EFDA–JET–CP(07)03/18* and *Proc. 34th EPS Conf. Plasma Physics (Warsaw, Poland, 2–6 July 2007)*
[8] Goodall D H J 1982 *J. Nucl. Mater.* **111–112** **11**
[9] Rubel M *et al* 2001 *Nucl. Fusion* **41** 1087
[10] Roquemore A L *et al* 2007 *J. Nucl. Mater.* **363–365** 222
[11] Yu J H *et al* 2008 Fast camera imaging of dust in the DIII-D tokamak *J. Nucl. Mater.* submitted
[12] Yu J H *et al* 2008 *Phys. Plasmas* **15** 032504
[13] Smirnov R D *et al* 2007 *Plasma Phys. Control. Fusion* **49** 347
[14] Rudakov D L *et al* 2007 *J. Nucl. Mater.* **363–365** 227

[15] De Silva A W 2000 *Contrib. Plasma Phys.* **40** 23
[16] Narihara K *et al* 1997 *Nucl. Fusion* **37** 1177
[17] West W P, Bray B D and Burkart J 2006 *Plasma Phys. Control. Fusion* **48** 1661
[18] Giovannozzi E *et al Burning Plasma Diagnostics Int. Conf. (Varenna, Italy, 24–28 September 2007) AIP Conf. Proc.* **988** p 148
[19] Han Y, Grehan G and Gouesbet G 2003 *Appl. Opt.* **42** 6621
[20] Smirnov R D *et al* 2007 *Phys. Plasmas* **14** 112507
[21] Tsytovich V *et al* 1989 *J. Plasma Phys.* **42** 429
[22] Bingham R *et al* 1991 *Phys. Fluids* B **3** 811
Bingham R *et al* 1992 *Phys. Fluids* B **4** 283 (erratum)
[23] Tsytovich V N and Morfill G E 2007 *EPS 2007* vol 31F(ECA) P-2095
[24] Behn R *et al* 1989 *Phys. Rev. Lett.* **62** 2833
[25] Bindslev H *et al* 2006 *Phys. Rev. Lett.* **97** 205005
[26] Castaldo C *et al* 2007 *Nucl. Fusion* **47** L5–L9
[27] Ratynskaia S *et al* 2008 *Nucl. Fusion* **48** 015006
[28] Morfill G *et al 1st Worshop on Dust in Fusion Plasmas (Warsaw, 8–10 July 2007)* http://cpunfi.fusion.ru/eps-dust-media2007/Morfill.............M2-2
[29] Burchell M J, Cole M J, McDonnel J A M and Zarnecki J C 1999 *Meas. Sci. Technol.* **10** 41
[30] Friichtenicht J F 1964 *Nucl. Instrum. Methods* **28** 70
[31] Grün E 1992 *Space Sci. Rev.* **60** 317
[32] Austin D E, Ahrens T J and Beauchamp J L 2002 *Rev. Sci. Instrum.* **73** 185
[33] Gault G E 1973 *Moon* **6** 32
[34] Jakubka K and Jüttner B 1981 *J. Nucl. Mater.* **102** 259
[35] Burchell M J, Kay L and Ratcliff P R 1996 *Adv. Space Res.* **17** 141
[36] Kistler S S 1931 *Nature* **127** 741
[37] Pierre A C and Pajonk G M 2002 *Chem. Rev.* **102** 4243
[38] Tsou P 1995 *J. Non-Cryst. Solids* **186** 415
[39] Brownlee D E *et al* 2004 *Science* **304** 1764
[40] http://www-amdis.iaea.org/ALADDIN
[41] Pugno R *et al* 2001 *J. Nucl. Mater.* **290–293** 308
[42] Burchell M J, Grajam G and Kearsley A 2006 *Annu. Rev. Earth Planet. Sci.* **34** 385–418
[43] Tsou P *et al* 2003 *J. Geophys. Res.* **108** 8113
[44] Morfill G and Jiansheng Hu 2008 private communication
[45] Voinier C, Skinner C H and Roquemore A L 2005 *J. Nucl. Mater.* **346** 266
[46] Parker C V, Skinner C H and Roquemore A L 2007 *J. Nucl. Mater.* **363–365** 1461
[47] Skinner C H, Hensley R and Roquemore A L 2008 *J. Nucl. Mater.* **376** 29–32
[48] Counsell G and Wu C H 2001 *Phys. Scr.* T **91** 70
[49] Counsell G *et al* 2006 *Rev. Sci. Instrum.* **77** 093501
[50] Liou J-C, Giovane F, Corsaro R and Stansbery E *Proc. 'Dust in Planetary Systems' (Kauai, Hawaii, USA, 2005)* (ESA SP-643, January 2007)