ELSEVIER

Journal of Nuclear Materials 266–269 (1999) 228–233

journal of nuclear materials

Dust in magnetic confinement fusion devices and its impact on plasma operation

J. Winter *, G. Gebauer

Institut für Experimentalphysik II, Fakultät Für Physik and Astronomie, Ruhr-University Bochum, D-44780 Bochum, Germany

Abstract

The formation mechanisms of dust particles in fusion devices and the possible interactions of dust with fusion plasmas are discussed. The growth of small particles in the plasma edge of fusion discharges is suggested in analogy to the well-known growth in reactive process plasmas (dusty plasmas). Results from the analysis of collected dust from TEXTOR-94 and first in situ observations by laser light scattering are presented, giving indirect evidence for some of the discussed mechanisms. Dust formation is an important PSI issue with serious potential implications and deserves future in depth studies. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Arcing; Dust; Impurity sources; Plasma edge; Redeposition; TEXTOR

1. Introduction

The existence of small particulates (dust) in fusion devices has been known for a long time. Particles are regularly found in the bottom areas of most tokamaks and stellarators. Ohkawa speculates in an early paper [1] on their impact on plasma operations, but no systematic investigations have been carried out.

Recently, the study of dust in fusion devices has become an important topic. One of the motivations comes from the ITER project, where dust is regarded as a potential safety hazard. Two different issues are being addressed: the confinement of radioactive material and the release of hydrogen due to reactions of the finely disperse dust with steam in case of an accident. A detailed discussion of these subjects is found e.g. in Ref. [2]. Since small carbon particles can retain large amounts of hydrogen, dust will influence the T inventory as well. Coordinated international efforts [3] are under way to establish a database on dust formation rates and size distributions from tokamaks and simulation experiments. This involves a standardized protocol for collection, statistical evaluation, and assessment of physical and chemical properties [4].

A related important task is the investigation and control of the dust formation mechanisms. Some of these processes are closely related to questions of erosion and redeposition of wall materials and to the stability and properties of the redeposited layers which may flake off the surfaces.

Another possible mechanism is the growth of small particles in the edge of fusion plasmas from atomic or molecular precursors which are released by physical or chemical erosion. As will be discussed in detail below the conditions in the edge plasma are very close to those of process plasmas in reactive gases. Detailed investigations exist on the formation, growth and plasma confinement of nano- and microparticles in these systems, see e.g. [5].

A third aspect is the possible impact of small particles on the operation of the fusion device and on the possible degradation of performance of the plasma discharge. A phenomenon common to all tokamaks are the so-called UFOs, particles entering the tokamak plasma and illuminating their path through the plasma by thermal glow and line radiation of ablated and excited atoms. They occur frequently during heavy plasma surface interaction. An impressive demonstration was given by Godall [6] using fast camera observations. The behaviour of big particles penetrating into the hot zones of the plasma is similar to that of fuelling pellets. It is well established that few big or frequent smaller events can lead to a

---

* Corresponding author. Tel.: +49-234 700 3693/3800; fax: +49-234 709 4171; e-mail: jw@plasma.ep2.ruhr-uni-bochum.de.

0022-3115/99/$ – see front matter © 1999 Elsevier Science B.V. All rights reserved.
PII: S 0 0 2 2 - 3 1 1 5 (9 8) 0 0 5 2 6 - 1

plasma disruption. In a recent paper by Narihara and co-authors [7] in situ experiments are described using the Thomson scattering set-up in JIIPT-2U to study the influence of small carbon particles with diameters <2 μm on tokamak discharges. The investigations were triggered by the occasional observation of very large scattering signals in the Thomson system which could not be explained by the plasma parameters. The statistics of the events and their correlation with abnormal plasma operation make it likely that they originate from light scattering of particles in the μm range. From experiments in which dust was dropped from the top of the machine into the discharge the authors concluded that an amount of about 10^6 particles of 2 μm do not affect a fully developed discharges, but that such particles existing in the main volume before start up lead to increased initial impurity concentrations. The authors state, that smaller particles might be present but escape their sensitivity and, in particular, that a careful investigation of the scrape off-region is necessary for a more detailed study.

2. Properties of dust in TEXTOR-94

The investigation of dust collected from TEXTOR-94 has been described in detail in a recent publication [8]. Only a brief summary is given here. The size distribution of the identified particles extends from about 100 nm up to the mm range. About 15% of the particles are ferromagnetic, independent of the size. The majority of the magnetic particles have a dark appearance. Scanning electron microscopy (SEM) with analysis of the composition by energy dispersive analysis of X-rays (EDAX) of the magnetic fraction shows, among irregularly formed species, a large number of almost perfect spheres with diameters between 0.01 and 0.1 mm which have a large iron concentration. Some of them exhibit a texture (Fig. 1), evidence for the formation of different phases. It is very likely that these particles were completely molten and that the phase separation occurred during resolidification. Also found are flakes of redeposited low-*Z*-layers with thickness up to 0.05 mm. Flakes with significant metal incorporation are ferromagnetic. Many flakes have a columnar growth structure and a porous, blister-like surface texture. The thicker ones show cracks across their surface. The non-magnetic fraction also contains whitish silicon rich particles. It is most likely that these particles were formed during silane injection experiments and Si-wall conditioning [9,10]. The third group of non-magnetic big particles is graphite crystals with well-established graphite grains. These clearly originate from fatigued graphite armor tiles. A significant part of the particles has dimensions below 1 μm. Some of them are agglomerates of individual particles of about 100–300 nm diameter, see Fig. 2. Their size and structure is consistent with what one would expect from plasma-induced growth [11,12]. The way the particles were collected in TEXTOR-94 does not allow the total quantity to be deduced, unfortunately.

3. Correlation of dust properties with 'classical' production mechanisms

As shown in the studies of Godall [6], heavy and sudden plasma-wall contact leads to the liberation of particles. Of particular importance in this context are disruptions, and the plasma contact with previously unexposed, i.e. deposition dominated, surfaces. The observations of the latter phenomenon [13] underline

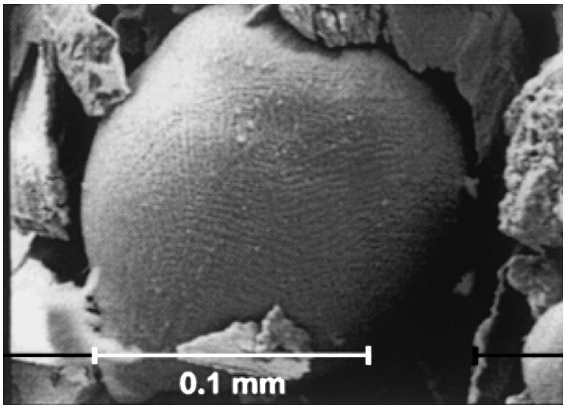

Fig. 1. Ferromagnetic sphere of iron showing domains of different phases.

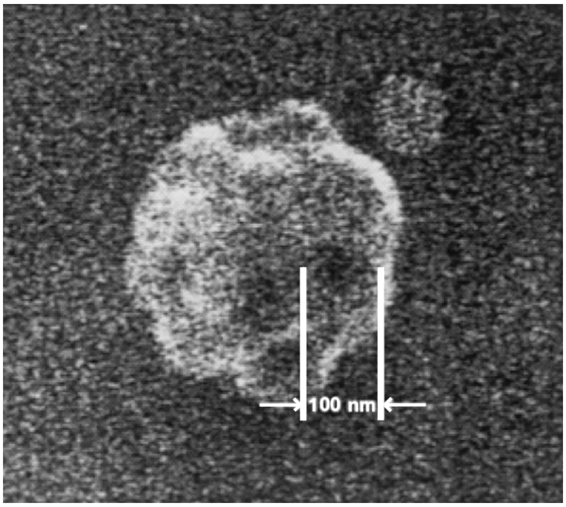

Fig. 2. Particle agglomerate of about 600 nm diameter, composed of several individual particles of 100–200 nm diameter. The appearance is consistent with growth in the plasma.

that redeposited films suffer from mechanical weakness due to stresses [14] and also from bad thermal conduction. Many of the flakes identified in the TEXTOR dust clearly originate from failed redeposited layers. Some of the very thin flakes may also be due to failed films from wall conditioning. The latter have a thickness of only several 100 nm. The adherence of these films is usually very good. They were observed to partly peel off, however, during venting of the vessel to air. They may then easily be liberated during plasma contact or as a consequence of mechanical shocks.

Unipolar arcs can liberate fairly large particles and droplets of molten metal. They could thus be a source of the observed metallic spheres. A more likely explanation is that these spheres were released during plasma surface interactions from the graphite limiters where they are formed by coalescence of a small metal coverage. Carbon is usually not wetted by metals. If a carbon surface becomes sufficiently hot the surface mobility of metal atoms is large enough to allow surface agglomeration. Examples for this mechanism can be found in the literature [15], see also Fig. 3. The primary source of metal atoms in TEXTOR-94 is likely to be arcing. Metal sputtering is unlikely because the Inconel liner is covered by thin protective layers from wall conditioning (siliconization, boronization). No metal surfaces are exposed to high heat loads in TEXTOR-94 under normal conditions.

The magnetism of some dust flakes which consist mostly of low-Z materials is due to codeposited metals. Although the arriving primary metal fluxes are very small as shown by collector probe measurements [16], a gradual enrichment of metal in redeposited layers may occur due to preferential chemical erosion of the metal-free carbon matrix.

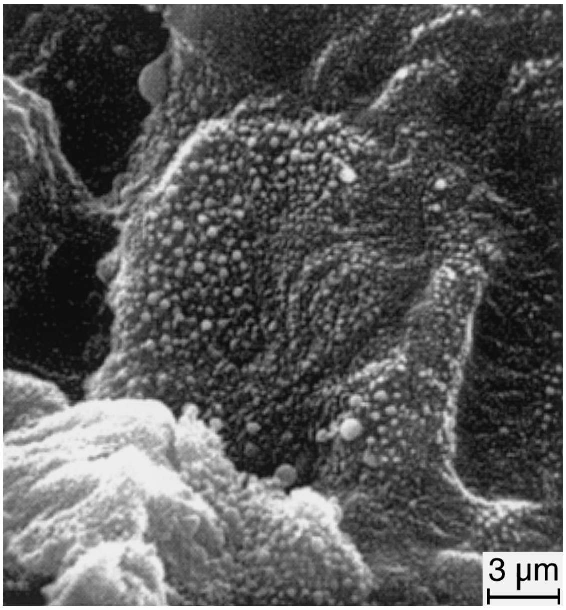

Fig. 3. Small metal drops on a graphite limiter (from Ref. [15]).

The wall conditioning procedures involving dc-glow discharges in He [11] or in reactive gases (carbonization, boronization, siliconization [17]) may lead to the formation of dust particles. Large positive and negative molecular ions with mass numbers exceeding 500 have been identified e.g. during laboratory experiments on carbonization [18]. In the case of DIII-D glow discharges in hydrogen have lead to the deposition of 'soot' on the surface which is believed to be disadvantageous for achieving high performance plasmas [19]. It is very probable that this soot is essentially small particles grown in the hydrogen glow plasma.

Most particles will fall to the bottom of the device at the end of a fusion plasma discharge. The lighter ones may be re-injected into the fusion plasma either by magnetic and also by electric forces when dust flakes are charged by plasma electrons. They may then be levitated close to the wall, see Section 4. Magnetic particles experience a B-force and may be sucked into the main vessel volume upon rising the toroidal magnetic field B_t. Plasma breakdown and burnthrough may be seriously impeded under these conditions. The fact that intense impurity radiation is observed during the start-up phase of most tokamak plasmas may be due to levitated dust. When the plasma is fully established particles are evaporated and the atoms ionized. They are lost to the wall after typically one particle confinement time.

4. On the growth of particles in the edge of fusion plasmas

The conditions in the deep plasma edge of fusion devices resembles closely that of reactive process plasmas. It has been well established, e.g. by sniffer probe measurements and spectroscopy, that the edge plasmas have a significant concentration of carbon and oxygen impurities, which, depending on the radial location may well exceed 10% [20]. This is particularly true for detached plasma conditions, in which the highly contaminated zones are more extended. Hydrocarbons, formed by chemical erosion, are the most important impurity source close to the wall. It should be noted in this respect, that Z_{eff} values close to 6 have been observed in the edge of high performance VH-mode discharges [21]. The typical plasma parameters in the deep edge, several scrape off lengths in the shadow of the limiters are electron temperatures below 5 eV and plasma densities of the order of 10^{17} m^{-3}. The plasma contains a large fraction of neutrals and has only an insignificant power flux along field lines. These conditions are very close to those of hydrocarbon process plasmas. Detailed studies of dust formation in hydrocarbon and silane plasmas exist. Several steps in their formation are distinguished: first the formation of macromolecules by multiple ion-molecule reactions followed by nucleation and agglomeration processes leading (in the case of silane) to nanoparticles of several 100 nm diameter [5]. As has been shown in a recent publication, there exist further agglomeration mechanisms driven by the thermal cooling of dust particles [22]. This mechanism starts at particle sizes of about 100 nm, finally leading to quasi spherical species with diameters exceeding 1 μm.

One important condition for the initial stage of dust formation is a sufficiently high residence time of the reactive species in the plasma. Negative ions play an important role in the case of silane and hydrocarbons. Negative ions are trapped by the plasma because they are repelled by the sheath potential. The same holds for nanoparticles which are charged negatively if their size exceeds a few 10 nm typically. The balance between electric force, ion drag force and weight determines whether the particle can still be suspended in the plasma. It should be noted that for typical experimental conditions of a process plasma ($T_e = 3$ eV), the charge on a sphere of about 1 μm diameter is of the order of 10^5.

Analogous processes are expected to exist in the edge of fusion plasmas. The formation of negative ions in the deep edge may well occur by electron attachment under the low-temperature conditions. The electronegativity of some C_xH_y ions is significant: $CH_2 = 3.39$ eV, $C_2H = 2.94$ eV. It has to be considered however, that a high flux of UV photons in the edge plasma tends to photo-detach the excess electrons. The balance of attachment and detachment rates will critically depend on geometrical factors and is difficult to assess a priori. As discussed in Ref. [8] negative particles are confined in the plasma edge: the sheath potential in front of surfaces repels them from the surface. Additional confinement in radial direction is provided by the magnetic field. A friction force from the background plasma is acting on these particles, driving them away from the stagnation point. Thus probable locations of dust particles will be close to limiter-like protrusions of the wall, where an effective trap from the superposition of these forces exists [8].

5. In situ laser light scattering measurements in TEXTOR-94

It is important to measure the behavior of dust particle in situ in order to test the above hypotheses. It is evident that the observation has to concentrate on the plasma edge region – it is unclear, however, where the location and what the spatial distribution and density of the particles is. Therefore a volume of the edge plasma as large as possible should be investigated with adequate spatial resolution in order to catch hold of the particles.

Similar to measurements in process plasmas [23] a laser light scattering set-up was realized at TEXTOR-94. Depending on the particle radius r, its refractive index n and the laser wavelength λ the light scattering of particles can be described by Mie-scattering (for $2\pi rn/\lambda \sim 1$) resulting in a complex intensity distribution, or by Raleigh scattering (for $2\pi rn/\lambda < 1$). For a crude first approximation one may assume isotropic scattering with the geometrical cross section $2\pi r^2$ (for $2\pi rn/(\lambda \gg 1)$. The signal at the detector is then proportional to $p\ (2\pi r^2)\ (\Delta\Omega/4\pi)$, where p is the laser energy density in the observation volume and $(\Delta\Omega/4\pi)$ is the solid angle of observation. It is trivial that large particles scatter more effectively than small ones. For a given laser power, a compromise has to be found between a large illuminated volume and a high laser energy density. The effective solid angle should be as large as possible. Since it is probable that the particles move in and out of the illuminated volume the continuous illumination of the observation volume is desirable to increase the probability for a 'hit'.

As a first step the system shown in Fig. 4 was realized. The beam of an Ar-ion laser (Uniphase) with a continuous power output of 70 mW at 488 nm was

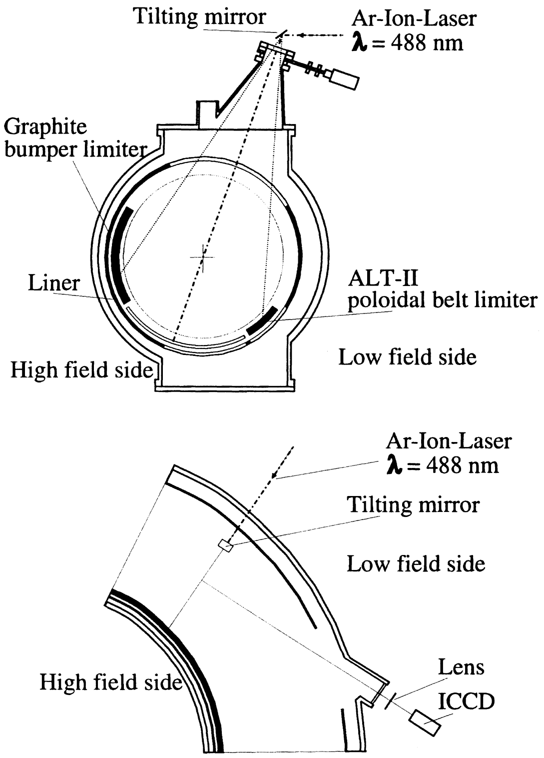

Fig. 4. Schematic experimental arrangement for the in situ observation of laser light scattering by dust in TEXTOR-94.

guided through a fiber to a tilting mirror on top of TEXTOR-94. As shown in Fig. 4 the mirror sweeps the beam back and forth across a poloidal cross section of the machine illuminating the area indicated in Fig. 4 at a rate of 100 ms per full sweep. In an improved version of the set-up an expansion optics of 150 mm focal length was used to widen the laser beam. Its width at the bottom of TEXTOR is about 20 mm. The observation of the scattered light perpendicular to the plane illuminated by the laser is made through a tangential port of TEXTOR-94, toroidally about 1.5 m away. The solid angle is about 3×10^{-4}. A CCD camera with light amplification and a narrow band interference filter (FWHM 0.9 nm) for the laser wavelength views almost the full cross section indicated in Fig. 4. Laser light directly reflected from the first wall components was eliminated by means of an aperture in the optical path.

First experiments without beam expansion were made in He and D_2 glow discharges at various glow currents. No signals due to light scattering by particles could be identified in this case. When the vessel was vented to nitrogen, however, clear scattering signals were recorded when the pressure in the vessel reached values of 400 mbar and higher. The scattering events were concentrated in the lower 1/3 of the vessel. The events are without doubt due to particles levitated from the bottom by gas convection. Pronounced scattering was also observed in the initial pump down phase from atmospheric pressure.

Attempts to measure scattering signals during the presence of tokamak discharges failed. The background intensity of plasma light at 488 nm is orders of magnitude larger than the intensity from the previously identified scattering events during the nitrogen vent. Using the expanded beam, unique but very few (frequency about 1/10 Hz) scattering signals from particles could be identified before the discharge initiation and also right after the discharge. All events occurred at the bottom 1/4 of the observation volume. Occasionally particles were seen to move in the illuminated volume for several video frames. Due to the bad statistics no correlation with the course of the discharge could be established so far. Automatic processing of the video data allowing the superposition of a large number of frames is important in order to improve the quality of information.

6. Conclusions

Small particles exist in fusion devices. The most important mechanisms for their formation appear to be: fatiguing and thermal overloading of wall components, flaking of redeposited layers which are mechanically weak and have a bad thermal conduction and the loosening and flaking of wall conditioning films after long exposure of the vessel walls to air. Evidence for these mechanisms is deduced from an analysis of dust from TEXTOR-94. Part of the dust flakes are magnetic due to incorporated metals. The metals may be enriched in the redeposited films due to a preferential reerosion of the carbonaceous matrix. Metallic spheres have been found which are most likely due to agglomeration of thin metal layers on hot graphite surfaces (limiters) and their subsequent release by plasma surface interactions.

An important additional ‘active’ mechanism of dust formation could be the growth of particles in the deep edge of the plasma itself from atomic or molecular precursors, in particular from hydrocarbons from the chemical erosion of wall surfaces. It is suggested that growth and confinement of these particles in the edge occurs in analogy to the well-investigated mechanisms in reactive process plasmas. The size and shape of the smallest particles identified so far is consistent with this mechanism. It is important to verify or disprove this mechanism because it may be of great importance for machines operating quasi steady state.

The formation of dust leads to material loss which is not fully accounted for by emission spectroscopy. Neutral atoms or molecules will be consumed in building up large clusters. These have their signatures in the infrared part of the spectrum which is usually not analyzed spectroscopically. Erosion rates may thus be higher than assumed so far.

It is speculated that particles will repetitively interact with many tokamak discharges because magnetic and electric forces levitate them.

First in situ laser light scattering experiments have identified dust particles during venting of TEXTOR-94 and before and after tokamak discharges. In all cases the events occurred at the bottom 1/3 of the poloidal cross section. This may be taken as an indication that particles are repetitively interacting with tokamak discharges. Although the attribution to light scattering from particles is unique, the bad statistics of these rare events does not allow us to deduce any correlation with different mechanisms or discharge phases. These experiments will be continued in future in a different geometry making use of the enhanced Mie-scattering amplitudes in forward or backward direction. This will increase the sensitivity of detection. In addition, we intend to employ data handling procedures allowing the superposition of long measuring sequences.

Acknowledgements

The authors gratefully acknowledge the help of A. Huber, A. Pospieszczyk, J. Schwarz and H.B. Schweer in setting up the laser light scattering experiment on TEXTOR-94. They appreciate many helpful discussions with V. Tsytovich.

References

[1] T. Ohkawa, Kako Yugo Kenkyu 37 (1977) 117.

[2] S.J. Piet, A. Costley, G. Federici, F. Heckendorn, R.Little, in: Proc. 17th IEEE/NPSS Symp. on Fusion Engineering, San Diego, vol. 1, Institute of Electrical and Electronics Engineers, Inc., Piscataway, 1998, p. 129.

[3] G. Federici, private communication and contribution at this meeting, 1998.

[4] K.A. McCarthy, D.A. Petty, W.J. Carmack, R.A. Anderl, in: Proc. IEA Tritium Experience Workshop, Princeton, NJ, 16–18 March 1998.

[5] Ch. Hollenstein, W. Schwarzenbach, A.A. Howling, C. Courteille, J.-L. Dorier, L. Sansonnens, J. Vac. Sci. Technol. A 14 (1996) 535.

[6] D.H.J. Godall, J. Nucl. Mater. 111&112 (1982) 11.

[7] K. Narihara, K. Toi, Y. Hamada et al., Nucl. Fusion 37 (1997) 1177.

[8] J. Winter, Plasma Phys. Contr. Fusion 40 (1998), 1201.

[9] F. Weschenfelder, J. Winter, U. Kögler et al., Plasma Phys. Contr. Fusion 38 (1996) A311.

[10] H.G. Esser, A. Lyssoivan, M. Freisinger, R. Koch, G. van Oost, F. Weschenfelder, J. Winter and TEXTOR-and ICRH-Team, J. Nucl. Mater. 241–243 (1997) 861.

[11] A. Garscadden, B.N. Ganguly, P.D. Haaland, J. Williams, Plasma Sources Sci. Technol. 3 (1994) 239.

[12] H.M. Anderson, S. Rodovanov, J.G. Mock, P. Resnick, Plasma Sources Sci. Technol. 3 (1994) 302.

[13] T.Denner, TEXTOR-Team, private communication.

[14] A.P. Martinelli, A.T. Peacock, R. Behrisch, J. Nucl. Mater. 196–198 (1992) 729.

[15] R. Behrisch, P. Borgesen, J. Ehrenberg et al., J. Nucl. Mater. 128&129 (1984) 470.

[16] P. Wienhold, J. von Seggern, H.G. Esser, J. Winter, H. Bergsaker, M. Rubel, I. Gudovska, B. Emmoth, J. Nucl. Mater. 176–177 (1990) 150.

[17] J. Winter, Plasma Phys. Contr. Fusion 38 (1996) 1503.

[18] A. Leukens, J. Winter, Verhandl. DPG (VI) 32 (1997) 266.

[19] G.L. Jackson, T. Taylor, private communication.

[20] V. Philipps, E. Vietzke, M. Erdweg, J. Nucl. Mater. 162–164 (1989) 550.

[21] G.L. Jackson, private communication.

[22] V.N. Tsytovich, Y.K. Khodataev, G.E. Morfill, R. Bingham, J. Winter, Comm. Plasma Phys. 18 (1997) in press.

[23] G.S. Selwyn, J.E. Heidenreich, K.L. Haller, J. Vac. Sci. Technol. A 9 (1991) 2817.