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Is Dust Formation a Concern for Fusion Devices?

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Abstract

Plasma-surface-interactions are responsible for the formation of small particles (dust) in fusion devices. This is particularly pronounced in devices with carbon wall materials. Though no major problem in present fusion devices, the large dust quantities generated in future machines are expected to be critical. The chemical reactivity and the retention of Tritium in carbonaceous dust makes it a safety hazard. Radioactivity leads to electrical charging of dust and to its interactions with plasmas and electric fields. This may have adverse effects for machine operations but can be used to advantage for particle removal. The paper will discuss mechanism for dust formation, dust characterization and address its expected behavior in fusion devices. New options for particle removal based on recent developments in dusty plasma research will be presented.

Keywords:

dust, dust removal, plasma-surface-interaction, erosion, redeposition, radioactivity

1. Introduction

When materials are exposed to high plasma loads, the emission of particles is often observed. In magnetic confinement fusion devices this leads to the so called UFO's, glowing objects moving through the plasma, heated up by the absorbed power. They can be readily observed by cameras [1]. In some cases the trajectories are influenced by an interaction with the magnetic field indicating that the objects are charged. Thus the observation of particle-plasma-interaction is not surprising to the physicist working at a fusion machine.

The major concern has been so far the triggering of disruptions, i.e. the uncontrolled loss of the stored plasma energy when solid particles get into the fusion plasma. Cooling of the plasma by dissociation and ionization losses and the excessive radiation from the ionized impurity atoms are driving mechanisms for disruptions. Narihara and coworkers [2] have shown that about 10^6 particles with a diameter $< 2\ \mu$m falling into a well developed discharge do not influence the plasma significantly. The discharge is rather robust. If particles are present in the start-up phase of the plasma they lead to increased values of $Z_{\rm eff}$ [2] with the disadvantage of high plasma resistivity and inherent instability. This can be compensated by an increased rate of current rise or by injection of additional heating power during start-up. The ionized impurities are lost within a few particle confinement times and stick to the wall.

Particles with dimensions in the range between a few nm and a few 1/10 mm (dust) are found on the bottom of many fusion devices. The particles collected from fusion devices with carbon wall components, TFTR, DIII-D, Alcator C-mod and from the Sirens simulator [3], have a size distribution centering around 1 μm. In the case of the DIII-D tokamak, the mass concentration was found to be in the range from 0.1–1 μgcm^{-2} on vertical surfaces, 10–100 μgcm^{-2} on the floor and lower horizontal surfaces [4]. The total amount is estimated to be between 30–120 grams [4] for several hundred discharges, corresponding to an integrated plasma exposure time of a few hours. This amount is

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still small and not of major concern. Particle formation and interaction with the plasma does not appear to be a critical problem in present devices.

In the framework of the ITER project it has become clear however, that additional aspects of dust formation are important for future machines [5]. They run long pulses and will have large plasma fluences. As will be discussed below in detail, some dust production mechanisms are proportional to the plasma fluence and are thus giving rise to dust inventories very much larger than those we find in present machines. Incorporation of hydrogen isotopes into dust will lead to large dust-bound Tritium inventories [6,7]. This is a major safety concern. Reducing the dust bound Tritium inventory in future machines has thus become a key issue.

This paper addresses some important open questions concerning the mechanisms, by which dust is formed, the characterization of the dust properties and the understanding of the behavior of the particles in the machine. Consequences arising from the radioactivity of dust, in particular electric charging and dust levitation in weak plasmas [8,9] will be discussed. Experiments have shown that plasma-levitated particles may be readily removed by appropriately shaped electric fields [10,11]. This may offer a novel solution for the removal of dust from fusion devices.

2. Transport of Wall Material

Graphite or carbon fiber composites are preferred materials for high heatflux components because of their good thermomechanical properties and their low atomic number Z. They are also considered for ITER. Carbon however suffers from large erosion rates due to a high physical sputtering yield and additional chemical erosion. Hydrocarbons are formed as a consequence of atomic and ionic hydrogen exposure from the fusion plasma and they are released from the surfaces into the plasma edge where they are dissociated and ionized and transported. As will be discussed in detail in a later section, the deep scrape – off layers (SOL) of a fusion plasma, i.e. the plasma regions close to the wall, may resemble closely hydrocarbon process plasmas.

A magnetic confinement fusion device is a closed system for condensable materials. Only volatile gases leave through the vacuum pumps at the end of a plasma pulse. Material eroded somewhere by plasma-surface-interactions is deposited at another place in the machine. The plasma strike zone on limiters and divertors which handle most of the heat- and particle outflow are usually dominated by erosion. The wall area which is further away from the confined plasma suffers a less intense heat and particle exposure and is deposition dominated. Depending on the gradients of the plasma fluxes, erosion and deposition dominated areas are often within a few mm of each other [12].

In the TEXTOR -94 tokamak for example, the average H (D) flux at the leading edge of the poloidal graphite limiter is 10^{23} m^{-2} s^{-1}. The averaged erosion yield (including both sputtering and chemical erosion) is 2×10^{-2} resulting in a primary loss rate of 2×10^{21} $m^{-2}s$ C atoms. This corresponds to a gross erosion of 1m per year at the limiter tip by regular plasma exposure. A large fraction of the eroded material is redeposited locally reducing gross erosion significantly (typically by a factor of 10) [13]. Some part of the eroded material however is gradually transported in multiple erosion-deposition processes from the erosion dominated to the deposition dominated areas [13]. Figure 1 shows a photograph of a poloidal limiter segment with the shiny erosion dominated top part and flaking redeposited carbonaceous material located on the curved sides of the limiter, just a few mm radially outward from the top.

Deposition of previously eroded carbon occurs in presence of fluxes of hydrogen isotopes. Hydrogen is incorporated (co-deposited) into the growing carbon layer. The properties of the redeposited layers vary strongly with the composition of the plasmas fluxes (H/C ratio), the ion energy at impact and the substrate temperature. Bombardment by energetic ions during deposition and high substrate temperatures tend to lower

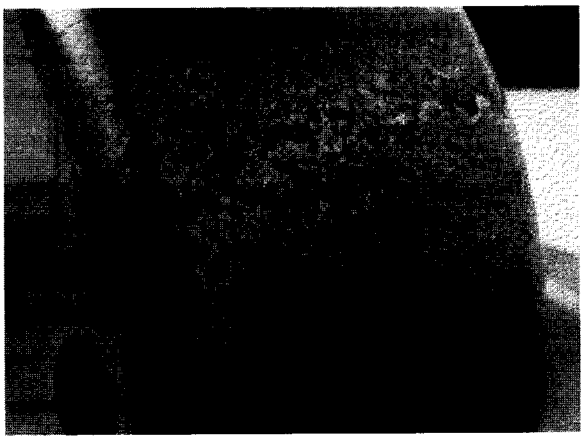

Fig. 1 Segment of the poloidal graphite limiter of TEXTOR-94 with the shiny erosion dominated zone (top) and redeposited flaking layers on the surface curved away from the plasma strike zone [courtesy J. v. Seggern [20], TEXTOR-94 team].

the hydrogen isotope concentrations. If the deposition occurs on cold surfaces via neutral radicals with insignificant energy the concentration may be as high as 2 H/C atoms. Modeling with the ERO-TEXTOR MC – code [13,14] of the erosion-redeposition processes at limiters in TEXTOR has shown, that important parameters for the amount and location of redeposition are the surface loss probabilities of C atoms and hydrocarbon ions or radicals. They can vary over several orders of magnitude for different species and flux scenarios [15]. Whereas ionic species dominate at the limiter or in the shallow SOL, the fraction of neutrals increases strongly in the deep scrape off-layer. Deposition from neutral radicals is becoming increasingly important here. Neutrals are not influenced by magnetic fields. Deposition may occur at positions, which are not reached by the magnetically guided ionic fluxes. Different sticking for reactive radicals, the importance of neutrals for the layer deposition and the transport of material due to repeated erosion and redeposition have been demonstrated in the magnetized toroidal plasma experiment TOMAS in which carbon film deposition from ECR plasmas in methane and acethylene was investigated [16]. Deposition from neutral radicals is also believed to be responsible for thick deposited layers on the cooled louvres of the JET divertor, quite remote from the plasma interaction zone [17].

Dust formation from carbon wall materials is particularly pronounced because of its large erosion rates. The estimates for the ITER dust inventory are several kg up to several 10 kg, depending on the operation scenario. The amount of Tritium trapped in the dust appears to be prohibitive. Dust formation rates and the specific tritium retention is expected to be much smaller when high heat flux components from the high-Z element tungsten are used. Whether the very low plasma impurity concentrations of high-Z material required for ignition of a fusion plasma can be realized is still unclear, however.

3. Dust Properties and Dust Formation Mechanisms

Redeposited carbonaceous layers have large stresses and a very poor mechanical strength, in general. They are usually brittle, delaminate from the substrate and fall off the surface as flakes [18-20]. Even if the layers do not fail immediately, this often occurs after a longer time, in particular after venting of the machine for maintenance or repair [21]. Many flakes have a columnar growth structure and a porous, blister-like surface texture. The thicker ones show cracks across their surface. Failed redeposited layers are the largest fraction in the dust collected from TEXTOR [18]. An example is shown in figure 2. A fraction of about 15% of the flakes is ferromagnetic due to incorporated metal atoms [18]. Although the material for the metallic structures inside TEXTOR is amagnetic stainless steel and inconel, the incorporation of sputtered metallic atoms and the loss of the phase structure leads to ferromagnetic carbonaceous dust particles. Spheres with diameters between 0.01 and 0.1 mm and with a large iron concentration are also found [22]. Some of them exhibit a texture, indicating different crystallographic phases. It is very likely that these particles were completely molten and that the phase separation occurred during resolidification. They may be due to splashed metal which was melted by excessive power loading during exposure to fast electrons or unipolar arcing. They may also be due to agglomerated metal atoms on hot carbon limiters. Metal atoms are first released by sputtering or evaporation, then transported through the plasma and finally deposited on the carbon limiters. Carbon is usually not wetted by metals. If the carbon limiter surface becomes sufficiently hot, the surface mobility of metal atoms becomes large enough to allow surface agglomeration [23]. The agglomerated spheres are finally relased by plasma-surface-interactions.

The ejection of whole graphite grains with diameters of a few μm may occur, when the material is weakened by repeated heating (thermal fatigue). Cracks

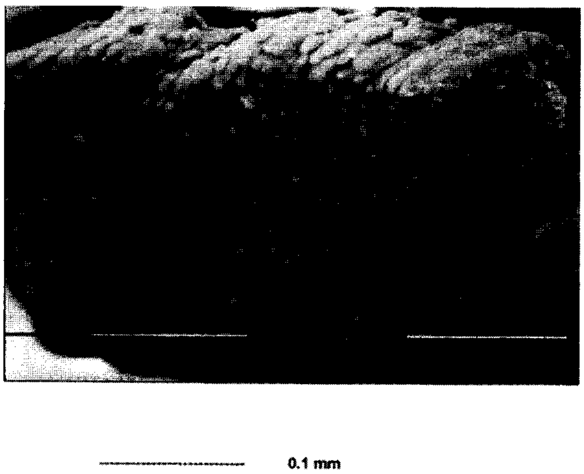

Fig. 2 Dust particle collected from TEXTOR-94

develop and propagate due to the thermally induced stresses.

For very high power fluxes from giant Edge Localized Modes (ELMs) or disruptions the ejection of debris and in particular evaporation or sublimation are dominant [24]. The vapor has a high density close to the surface and the vapor particles have a short mean free path. Coagulation processes from supersaturated vapor leads to the formation of small particles with average diameters of several 10 to 100 nm. This mechanism was verified in a laboratory experiment in which different carbon materials were repeatedly exposed to power loads of 0.5 – 1.5 GW m^{-2} using a high power electron gun [24]. Transmission electron microscopy of the released material shows small globular clusters, see figure 3, and also evidence for the formation of fullerene like materials. A similar type of particles was identified in the TEXTOR dust (figure 4) consisting of agglomerates of individual globular particles of about 100 nm diameter. They may have been formed by coagulation from C vapor during arcing, ELMs or disruptions. In Tore Supra fullerenes and nanotubes were identified in the collected dust [25]. In Extrap rounded particles are found which were partially ablated while moving through the plasma [26].

Another mechanism for the formation of the very small particles in fusion devices with carbon wall materials is their growth in the cold plasma regions close to the wall or in a detached divertor. These plasmas have electron temperatures as low as 1–2 eV and a high concentration of neutrals with a large fraction of hydrocarbons from chemical erosion. The total gas pressures go up to a few Pa. The measured local hydrocarbon concentrations can be in excess of 10% [27]. These conditions are close to those of a process plasma where dust formation has been observed by multiple ion-molecule reactions and agglomeration processes [28,29].

Figure 5 shows the mass spectra of positive ions, neutrals and negative ions which are formed in the bulk of a glow discharge process plasma in methane which is operated at pressures of about 1 Pa. Details of the experiment are reported elsewhere [30]. The equilibrium gas composition is about equal parts of H_2 and CH_4. The mass resolution was set to 12 atomic mass units such that going from one maximum to the next corresponds to the addition of another carbon atom to the previous molecule. It is evident from figure 5 that very large species are growing in the plasma. The mechanism is via repetitive reactions between an hydrocarbon ion and a neutral hydrocarbon molecule. The formation of large negative ions is particularly pronounced. Negative particles are well confined in the potential well of the glow discharge and thus have a large residence time.

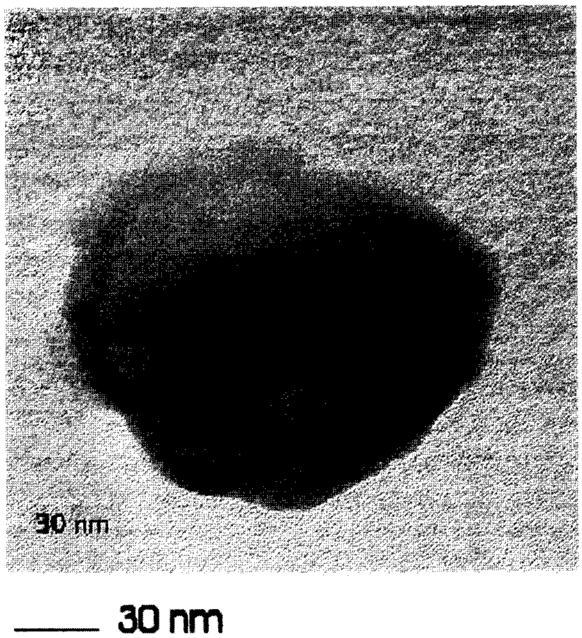

Fig. 3 Globular particle from agglomeration of supersaturated C-vapor [24].

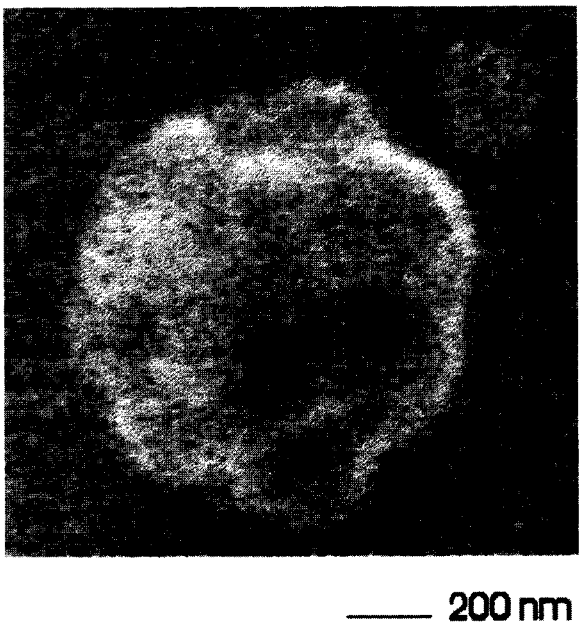

Fig. 4 Agglomerate of globular nanoparticles from the TEXTOR- dust.

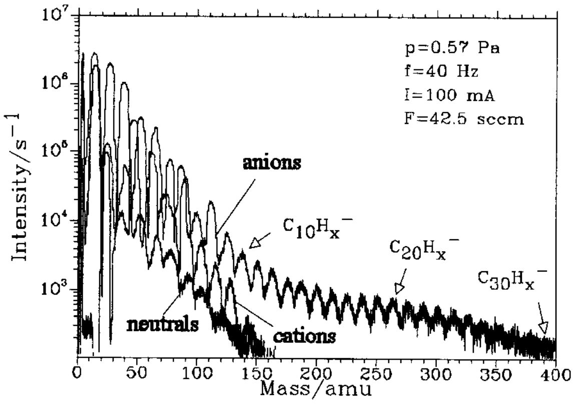

Fig. 5 Mass spectra with low resolution of positive and negative plasma ions and of neutrals from a DC glow discharge in methane.

The growth process is so rapid, that even the limited residence time of the positive ions is long enough to allow breeding of cations with mass 150 in this experiment. Detailed analysis of the negative ion spectra reveals the growth of large linear chains (up to about n = 10 C atoms) in the initial stage, then the collapse to ring structures (for $10 < n < 20$) and the three dimensional collapse and isomerization towards fullerenes for $n > 20$ [31], in full agreement with molecular stability calculations [32,33]. Big ions can be identified already 50 ms after the start of the discharge.

As has been discussed elsewhere [18], once negative ions are formed by dissociative electron attachment, they are well confined in the edge of a fusion plasma. Since C_1, C_2, ..C_n clusters and several C_xH_y radicals exhibit a high electronegativity (CH_2 = 3.39 eV, C_2H = 2.94 eV) these species are rather stable against electron detachment. Direct experimental evidence for such dust growth processes within the edge plasmas of fusion devices is not available yet. Because of their potential importance, they deserve increased attention, however.

Dust formation by flaking of redeposited layers and the growth of particles in the plasma edge are both proportional to the plasma fluence. They are thus of importance for future long pulse devices. Dust formation mechanisms based on evaporation or particle ejection due to thermal overloading and off- normal operation can in principle be avoided by good engineering and operation scenarios with wide safety margins.

4. Radioactive Dust Particles and Dust Removal

For the following considerations we assume a carbonaceous particle of 1 μm thickness with a diameter of 5 μm with a total concentration of hydrogen isotopes of 0.4 per C atom of which 50% is Tritium. The mean density of such type of redeposited carbon film is assumed to be 1.5 gcm^{-3}, a value found for redeposited a-C:H layers in the deep scrape off-layer of TEXTOR [34]. The total number of T decays in the carbonaceous particle is then about 5×10^2 s^{-1}. If all electrons leave the particle into the vacuum, the steady state positive charge on the particle will depend on its effective neutralization rate which is unknown a priori. Since hydrogen saturated carbon films are often good insulators, a significant charge may accumulate. 500 elementary charges suffice to levitate our particle in an electric field E = 38 Vcm^{-1}. Electrostatic repulsion of particles due to radioactive charging and jump-up against gravity has been observed during the Tritium clean down of TFTR, for instance [35].

Another effect associated with the radioactivity of particles is the formation of a "nuclear induced plasma" in which levitation of particles has been observed [8-10]. A nuclear induced plasma is formed by products of nuclear reactions traveling through a gas and producing electron-ion pairs in their tracks as well as excited atoms and molecules. Dust particles placed into a nuclear induced plasma, are affected by flows of electrons and ions. Due to the different electron and ion velocities the dust particle has a negative average charge in equilibrium. Since several mechanisms are responsible for the charging of a radioactive particle, the sign and quantity of the charge may vary. Nuclear induced plasma were produced near atmospheric pressures by alpha-particles and fission fragments from a thin layer of ^{252}Cf and by neutron activated radioactive CeO_2 particles undergoing β-decay [10]. Plasmas were induced in neon and argon at subatmospheric pressure in the range from 0.25×10^5 Pa up to 10^5 Pa between two parallel metal electrodes in a cylindrical glass chamber. Melamine- formaldehyde (MF) particles and cerium oxide (CeO_2) particles were introduced into the plasmas. Conical structures of levitated CeO_2- and of MF-particles near a hole in the upper electrode were observed when this electrode had a positive polarity. Figure 6 presents a video image of the conical structure. Charges of the levitating dust grains were estimated from a balance of the gravitational force and the electric force to be in the range from 200 **e** up to 400 **e**. In the

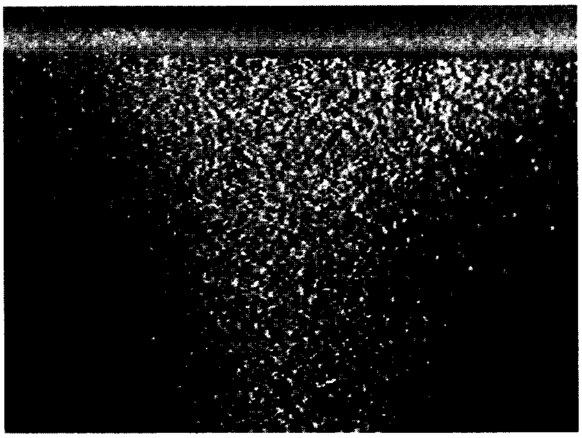

Fig. 6 Conical structure of a plasma suspended particle cloud.

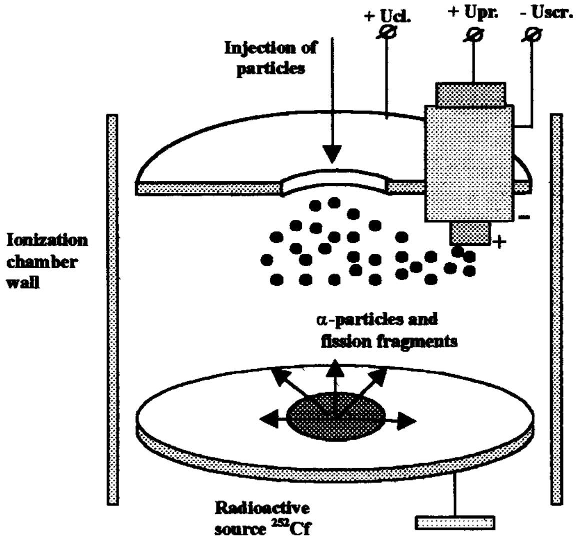

Fig. 7 Schematics of the electrode arrangement for particle removal from a dusty plasma.

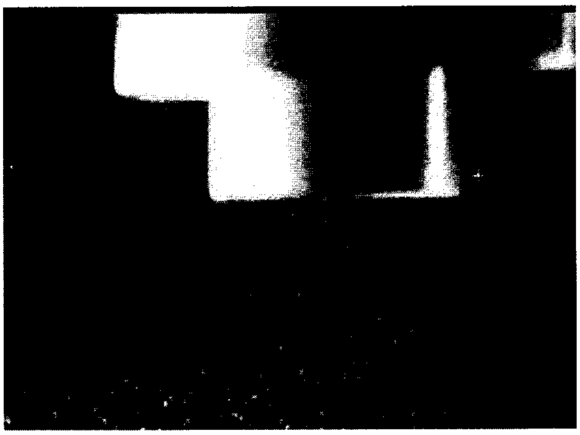

Fig. 8 Video image of dust particle removal by the electrode arrangement shown in fig.7.

case of the reactor-activated CeO_2 particles, broad regions with levitating dust in the central part of the interelectrode space were observed when the electric field was less than 30 V/cm. These experiments on dusty plasmas in a radioactive environment demonstrate that radioactive particles may be levitated in weak plasmas and that it is possible to control their position by means of electrodes.

To remove charged dust grains from the volume of the experimental chamber an electrostatic probe was developed, the so-called "plasma vacuum cleaner" (fig.7) [10]. It is a probe consisting of two electrodes: the main electrode on positive potential and the screening electrode on negative potential. Both electrodes generate the electric field which induces a flow of negatively charged dust grains from the plasma into the probe. Figure 8 shows a video frame demonstrating the removal of dust grains from the plasma volume.

5. Some Effects of Dust on Fusion Devices

Most dust particles fall to the bottom of the device. After some operation period a significant reservoir will have accumulated. Since the dust is mobile it may well fill gaps of the complex in-vessel structures which were designed for functional reasons and thus lead to failure and malfunction. The heat transfer to cooling structures is strongly impeded by a dust layer on top.

Small particles may be re-injected into the fusion plasma by magnetic and also by electric forces when dust flakes are charged by plasma contact. They may then be levitated close to the wall. Magnetic particles experience a ∇B-force and may be sucked into the main vessel volume when the toroidal magnetic field is switched on. The charging of dust due to the radioactive decay of Tritium may lead to additional complex effects. During break down and in the initial current ramp phase of a fusion plasma rapidly varying eddy currents are flowing in the vessel. They cause electric fields whose strength and direction is difficult to predict. The electric field strength may be large enough to levitate the charged dust particles. If these particles get into the main volume of the vessel before a significant current is established, burnthrough of the plasma becomes difficult because of high radiation losses. Compensating for this in future devices by more ohmic heating power is difficult, because particularly low loop voltages (of the order of 1 Volt) are required for the sake of the superconducting coils.

Dust particles are a sink for electrons. The charge on a dust grain is about 10^3 elementary charges for a 1 μm diameter particle per eV electron temperature, increasing with particle size and electron temperature. The heavy negative particles may change the dynamic response of the edge plasma e.g. to low frequency acoustic waves. There are a number of forces acting on particles in a plasma: electrostatic forces due to their charge and the local electric field, drag forces by the streaming ions, thermophoretic forces, gravitation etc. Thus fine particles can be transported far away from their point of origin unlike e.g. massive splashes of molten metal, which are deposited close by.

Spectroscopy of the emitted light from excited atoms or ions is a widely used method to measure erosion rates of the wall material. If radiative states of the species are bypassed by early clustering and agglomeration, the values derived from spectroscopy may be incorrect.

It is likely that a nuclear induced plasma is formed in the vessel when the pressure is increased to about 10^{-3} mbar for plasma breakdown. The range of the electrons is of the order of 10^3 m at this pressure. Due to the toroidal magnetic field of 5–7 T the electrons are confined and can ionize the gas efficiently. A rough estimate [10] yields a density of the nuclear induced plasma of the order of 5×10^9 cm^{-3} which is dense enough for dust levitation.

6. Conclusions

The existence of dust in fusion devices is a fact. Dust does not seem to be a major concern in present machines. This may be different in future devices. It is important to assess carefully the impact of dust on safety, plasma performance, machine operations and design of these machines. Because of the long pulses dust generation mechanisms which are proportional to the plasma fluence (erosion/redeposition, growth in the plasma edge) are of particular concern. Dust charging by radioactivity and the formation of a "nuclear induced plasma" are aspects which have to be considered carefully. A novel technique for dust control bases on dust levitation in weak plasmas and particle removal by appropriately shaped electrodes. In situ measurements on dust behaviour in present fusion machines are very important. Bringing together the expertise from fusion research, low temperature plasma physics in reactive gases and dusty plasma physics may help to successfully tackle such an important and demanding task.

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