Physics – Uspekhi **41** (8) 815 – 822 (1998)

PHYSICS OF OUR DAYS

PACS numbers: **28.52.–s**, 52.40.Hf, **52.55.–s**, **81.90.+s**

On the role of dust in fusion devices

V N Tsytovich, J Winter

Contents

1. Introduction	**815**
2. The present state of the problem	**815**
3. Problems to be solved	**819**
4. Dust agglomeration	**820**
5. Recent experimental data on analysis of dust in controlled thermonuclear devices	**821**
6. Historical comment and conclusions	**822**
References	**822**

Abstract. **The problem of dust in the vicinity of the walls of Controlled Thermonuclear Devices (CTD) is discussed. It is pointed out that the conditions in the scrape-off layer and divertor are similar to those in low-temperature plasma processing devices where dust is a common occurrence. In the absence of *in situ* dust diagnostic techniques for present day CTD plasmas, indirect indications of the possible role of dust are analyzed. The most recent data on after-discharge dust suggest that during a discharge dust is confined for a long time inside the edge plasma. It is emphasized that the CTD dust problem assumes more significance for future larger power loadings and longer operation times expected for new devices such as ITER.**

1. Introduction

Let us firstly remind the reader what is usually meant by dust particles in plasmas: the dust particles are small solid macroparticles embedded in the plasma. One important characteristic size in a plasma is the Debye radius, the distance over which the field of any charge in the plasma is screened. The dust particles can have a size smaller or larger than the Debye radius, but most often their size is less than the Debye radius and this we will have to keep in mind in what follows.

Any solid body embedded in a plasma is soon highly negatively charged since the thermal electron velocities are much higher than the ion thermal velocities. The dust particles usually have large charges of the order or larger than 10^4 electron charges and even a small concentration of them can influence the electrostatic balance and their contribution to the local quasi-neutrality conditions can be important. They also make the plasma a highly dissipative system since the plasma recombines on dust particles.

At a first glance dust particles can not survive for a long time in a plasma due to the relatively high plasma temperature. In general this statement is incorrect. Numerous experiments show that dust particles can not only survive in a plasma but can form and grow inside the plasma. For this the plasma temperature should be not very high. Even in the first experiments with low-temperature plasma, Langmuir noticed the presence of a large amount of dust particles. An important point is that the low-temperature plasma is usually in contact with the walls from which not only a gas component is ejected but also the macro-particles. The latter is related to complex structure of the surfaces and to the inhomogeneity of the plasma flux to the walls. The problem of plasma – wall interaction has been intensively tackled in recent years. The result of these investigations is that any contact of plasma with the walls lead to a certain extent to the injection of dust particles into the plasma. Even in the case where the dust particles disintegrate in the plasma volume a balance is usually established between the injected flux of dust particles and their disintegration far from the walls in the way that the concentration of dust particles at a certain level is established at the edge plasma. At the present time it becomes clear that most low-temperature plasma experiments deal with plasmas in which dust plays an important role.

The physics of dust in a plasma is more developed (theoretically, experimentally and computationally) for the case where the size of the dust particles is less than the Debye radius. We will use this assumption in the estimates given below.

2. The present state of the problem

The accents of investigations in the program of controlled thermonuclear research have recently changed substantially. Amazing progress has recently been made in controlled thermonuclear fusion research. Plasma heating has been achieved up to temperatures an order of magnitude higher

V N Tsytovich General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 117942 Moscow, Russia
Tel. (7-095) 135 02 47; Fax (7-095) 135 02 70
E-mail: tsytov@td.lpi.ac.ru
J Winter Institut für Experimentalphysik II (Anwendungsorientierte Plasmaphysik)
Ruhr-Universitat Bochum, D-44780, Bochum;
Institut für Plasmaphysik, Julich GmgH, IPP, 52425, Julich, Germany
Tel. +49 (0) 234 700 3800/3693; Fax +49 (0) 234 7094 171
E-mail: jw@plasma.ep2.ruhr-uni-bochum.de

Received 5 January 1998
Uspekhi Fizicheskikh Nauk **168** (8) 899 – 907 (1998)
Translated by V N Tsytovich; edited by L V Semenova

than the temperatures in the center of the sun, and plasma densities and energy confinement times close to the values for thermonuclear reactions with a positive energy balance have been realized. At the present time therefore, investigations in the problems of CTD have substantially shifted to the problems of interaction of high energy flux with the walls and to the problem of the so-called first wall where large energy flux created by thermonuclear burning contact the walls of CTD. One main problem of CTD remains the control of plasma – surface interactions under the influence of large energy flux to the walls, which are characteristic of fusion burning plasmas. Aspects of material science are important in this area. But obviously these problems make it necessary to control the properties of the plasma close to the walls. As we will discuss below, it appears that new physical phenomena have to be carefully considered, namely the interaction of the edge fusion plasma with small particles (dust) which can form dust-plasma layers in edge plasmas. The plasma flux then will interact not directly with the wall but will be changed by dust-plasma layers appearing as result of plasma – wall interaction. This can induce a dramatic change of confinement and transport phenomena for large energy flux and large confinement times due to the larger role of such dust – plasma layers in edge plasma.

In this paper we will discuss the indirect experimental evidence for the presence of dust – plasma layers in the edge plasma of present CTD.

We start with explaining why the dust is created in the edge plasma and what the mechanism of dust confinement is.

The present thermonuclear program is essentially based on magnetically confined plasmas in tokamaks. Thus we discuss the appearance of dust in tokamaks.

First of all we mentioned that in the core of CTD solid particles cannot survive and will soon evaporate. Widely used is the method of increasing the plasma densities by injection of pellets into the central plasma regions where they evaporate and increase the plasma densities. These pellets, although much larger than the size of solid particles called dust, evaporate very fast during their passage through the plasma of the central part of CTD. We distinguish pellets and dust particles since usually the term dust particle is used for solid particles of size less than the Debye screening radius, while pellets have sizes larger than the Debye radius. The physical processes of evaporation of small solid particles are different for dust particles and pellets.

The hot plasma part of tokamaks exists up to the last closed magnetic surface. This part is called the confinement region. Although at the edge of the confinement region the plasma temperature is lower than in the center of the plasma torus, it seems still to be high for macro-particles (dust) (which may appear for some reason in this region) to survive for a long time. Usually dust particles can survive for a long time in plasmas with temperatures less than 20 eV. But there are regions behind the last magnetic surface where the temperatures of plasma are even lower and these regions can influence the confinement of plasma inside the last closed magnetic surface. The region behind the last closed magnetic surface is called 'Scrape-Off Layer' (SOL) since the plasma is scraped off in this region either to the chamber walls or to a limiter or divertor. Observations show that usually in a SOL strong turbulence is present, the diffusion is rapid and the temperature gradients are large. Close to the walls the plasma temperature reaches values of the order of a few eV and in these regions dust can easily survive. In fact we will give experimental evidence that dust exists in these regions inside the edge plasma and is not located on the walls. This evidence is indirect since it comes from analyses of the dust collected after the discharges. But the size and shape distributions of dust particles and their material constitution indicate that during the discharges dust must be confined in the low-temperature parts of edge plasma and is exposed to the low-temperature plasma during the whole discharge.

In this context it is important to note that future CTD should operate continuously whereas the present devices operate for several tens of seconds. In planning future fusion devices two important extrapolations from known devices are made: it is expected that the confinement time and the energy losses will follow the same empirical laws although the power of the energy flux to the walls is much larger, and it is expected that the same empirical law applies for a much longer operation time. The question is what the change in plasma – wall interactions for large operation times can be. We can expect that the longer the discharge time and the larger the energy flux the larger the influence of the dust present in the edge plasmas. Evidence for this is given by most plasma etching experiments and plasma processing.

Thus we would like to compare the plasma parameters in etching experiments with those in edge plasma of CTD.

The walls can evaporate and inject into the plasma not only neutral particles (gas) but also some solid parts of the wall, which may be considered as injection of dust particles. It is important to note that the power flux in future CTD will be much larger and again one can expect that the plasma – wall interaction will create a larger dust particle flux from the walls.

This expectation has also been derived from known etching experiments. In etching experiments the plasma parameters are similar to those of an edge tokamak plasma. The plasma density is not as high as in tokamaks — it is about $10^9 - 10^{10}$ cm^{-3}; the electron temperature is between 2 eV and 5 eV, but the operation time is hours to days. This means that we are able to make a reasonable estimate of the role of dust for long operation times in CTD using the etching data. In etching experiments the ionization in the volume is often produced by an external source such as HF radio fields while these fields are absent in CTD, if external HF heating is not used. Nevertheless the most important observation is that the creation of dust flux from the walls and the continuous growth of dust particles inside the plasma is a common phenomenon observed in etching devices. The products of etching are usually injected into the plasma volume and form dust particles with rather large charges created by plasma currents. The charge of dust particles Z_{d} in units of electron charge for a 1 μm $= 10^{-4}$ cm size dust particle is of the order of 10^4. Due to the large charges the potential energy of the dust particles in an electron potential of about 3 V is $3 \times Z_{\mathrm{d}}$ V (about 30 kV for $Z_{\mathrm{d}} \sim 10^4$). This is a large potential well for the dust particles which have a rather small kinetic energy in these devices. Therefore the dust is usually embedded in the plasma and is levitated in the DC electric fields formed in the plasma sheath close to the walls and is well confined in the plasma volume. This confinement is related to the large dust charges and the presence of electrostatic fields in the sheath layer close to the wall.

The etching experiments show that the dust particles continuously grow while being confined in the plasma volume. There are two mechanisms of dust formation: the first is the ejection of macro-particles from the walls and the second is the condensation of materials from over-saturated vapors of complex molecules and molecular clusters. The second process starts with the chemical formation of complex molecules and clusters. The successive ion-molecular reactions then finally lead to the formation of dust particles. Recent reviews on the formation of dust in etching devices are given in Refs [1 – 3].

Measurements of the near wall plasma parameters in the SOL of CTD show that similar conditions can also exist there. The temperature of the electrons in the plasma detached from the divertor close to the walls of CTD can be as low as 1.5 eV [4] although the density is larger — of the order of $(10^{14} - 10^{15})$ cm^{-3}. The ion flux in the detached divertor plasma is very high (2×10^{20} cm^{-2} s^{-1}). This creates a very intense sputtering of the walls. In a detached limiter plasma the electron density is lower, $n_e \sim 10^{12}$ cm^{-3}, and the electron temperature is a bit higher, $T_e \leqslant 3$ eV. The dust particles can survive well and grow under these conditions. Moreover, many of the present devices use low Z carbon materials for covering the surfaces of wall components, limiters and divertors which meet the high heat flux. The erosion yields of these surfaces are rather high: the sputtering erosion yield is of the order of 10^{-3}, and the chemical erosion yield of the graphite armor is 2×10^{-2} leading to the formation of hydrocarbons and other volatile molecules seeding the edge plasma. The formation of C_yH_x complexes up to $y = 30$ has been observed by optical measurements in edge plasmas. As was mentioned, in etching experiments one of the mechanisms of dust formation is related to the formation of molecular complexes which precedes the dust formation. Measurements (showing that during the film deposition complexes are formed [5] up to $C_{30}H_x$ and that they are present on the films to start the dust formation after evaporation) indicate that similar dust formation mechanisms in their initial stage are observed in CTD. One can compare the CTD observations only with the initial stage of etching experiments since the etching experiments have much longer durations than the CTD discharges. But in the future CTD should work continuously and one expects this process to proceed in the same manner as in etching experiments.

For the detached plasma conditions mentioned above the flux of CH_4 from the wall is 3×10^{18} cm^{-2} s^{-1} and close to the wall the ratio of the density n_{CH_4} to the electron density n_e is 5%.

It should be mentioned that the advanced wall conditioning techniques applied to fusion devices utilize a coating of the wall with carbon, boron or silicon (carbonization, boronization or siliconization [5]). One aspect is that with this coating the plasma – wall interactions in CTD become almost the same as in plasma processing devices using carbon and silicon materials, in which the formation of dust particles is frequently (or more exactly inevitably) observed. Thus the continuous formation and growth of dust particles in discharges in CTD with carbon, boron or other wall coatings are very probable, and both mechanisms of dust formation mentioned in relation to etching experiments can work in CTD. The recent indirect experimental evidence for the existence of dust inside the edge plasma in CTD is described below.

An important difference between the edge plasma of CTD and etching plasma is the presence of a high level of turbulence in the edge plasmas of CTD. This can significantly increase the dust formation in CTD compared to etching devices. As in most etching experiments the plasma – wall interactions in CTD are not only related to wall evaporation and the injection into the plasma of neutral species but, in addition, to the injection of some small parts of the material of the walls as macro-particles (dust). This process can be more effective in CTD due to the instabilities in the flux close to the wall. It is well known that the so called saw-tooth activity or presence of the edge localized modes in divertor devices are responsible for large periodic excursions of power flowing to the high heat flux components. The walls can suffer significant thermal fatigue and small scale surface disintegration when grain ejection occurs. This will be enhanced by the occurrence of hydrogen induced embrittlement. Thus the instabilities in edge plasma can increase the flux of dust injected into the edge plasma.

In current tokamaks a very large power loading of the wall surfaces already occurs during disruptions. Often dust particles are indeed observed during disruptions by their optical traces (but only the largest dust particles can be detected this way). This phenomenon was first called 'UFOs' (Unidentified Flying Objects) in CTD although now it is identified as large dust particles. The distribution of dust particles by size created during disruptions is unknown since only the largest dust particles can be observed as UFOs and there could many more dust particles of smaller size be created during disruptions.

Note that the dust particles created in disruptions are accumulated from different disruptions and also from one discharge to another. When the next discharge starts the dust particles created in previous ones may be reinjected into the plasma volume levitating close to the walls.

After operation of CTD the dust particles are usually found in the bottom area of the fusion devices. Thus there is no question about the presence of dust in CTD but the question is whether during the discharges most of the dust particles are embedded in the edge plasma or attached to the walls. For the case that they are confined in the plasma they can influence not only the total heat transfer, and create an additional impurity flux but can also play an important role in the general problem of the plasma – wall interaction and the problem of energy outflow. From the amount of dust found in the current CTD after operation one can estimate the expected dust production by the new CTD such as the planned ITER. This estimate is 1 ton of dust per year. The dust in ITER will be radioactive, accumulating radioactive tritium. In this context many safety problems will arise which need to be solved. A recent review of these problems can be found in Ref. [6].

Let us briefly discuss the physics of dust charging and the dust – wall interaction. The dust particles formed are rapidly negatively charged if the charging is produced by plasma currents. The particles can be charged positively if the electron losses due to the photoelectric effect caused by UV plasma radiation exceed the electron plasma charging current. The charge on a dust particle in the case it is charged by plasma currents is mainly determined by the electron plasma temperature and the size of the dust particle. The surface dust potential will differ from the electron temperature (both in energy units) by some numerical factor of the order of 1. This potential is known as the floating potential and corresponds to zero plasma current on the dust particle. A micron size dust particle for an electron temperature of several eV has a charge $Z_d \sim 10^4 - 10^5$ electron charges. The charge of the dust particle is proportional to its size, and thus only very small dust particles will have a charge of the order of several electron charges. These negatively charged particles will be trapped by the electric field of the plasma sheath close to the wall. The appearance of the sheath is due to the same process as the dust charging. The electron thermal current is larger than the ion thermal current due to the mass difference between electrons and ions, and both the wall and the dust particles will be negatively charged until most of the electrons except the fastest ones are reflected from the wall or from a dust particle while the electron and ion currents become equal. The difference between the wall and the dust particles is a relation between the size and the Debye radius. The dust particle size is usually much less than the Debye radius while the wall curvature radius is much larger than the Debye radius. The plasma potential drop close to the wall (related to the plasma sheath) may be $\phi \approx 3.8 T_e$ and is of the order of $4-20$ V. The dust particle confinement potential will then be $Z_d \phi \sim (4-20) \times (10^4 - 10^5)$ V. The force in the sheath related to this potential is sufficient to compensate gravity and the ion drag force appearing due to the presence of an ion flux in the sheath close to the wall. The ion flux appears due to the negative potential of the wall. Thus the dust particles may levitate both at the bottom of the discharge where gravity and the ion drag force are in the same direction and on the top of the discharge where the ion drag and gravity are in opposite direction. Since the drag force is proportional to the square of the dust size (proportional to the dust surface), and the gravity force is proportional to the cube of the dust size (to the mass) there will be a critical size where the gravity exceeds the drag force and in the upper part of device only the dust particles with sizes less than the critical will be forced to the walls. In any case one should expect the presence of dust layers close to most of the walls of CTD with some variations of charges along the surface.

There is even deeper physics related to the presence of the dust layer close to the walls in an edge plasma. The plasma close to the walls and the hot plasma inside CTD are not independent of each other. At first glance one may think that these dependencies are not strong and that one can, for example, change some properties of the edge plasma without disturbing the hot part or vice versa. But this appears to be not correct. First of all the heat flux which exists inside the hot part of the plasma volume and the heat flux in the plasma near the wall are the same since the flux of energy is conserved. Thus the edge plasma must transfer all the energy flux created inside the hot plasma of CTD. On the other hand there are clear indications that the properties of the edge plasma influence the confinement and thus the properties of the hot plasma core, although these processes are presently not fully understood. The most probable statement is that the edge plasma serves as some kind of boundary condition for the hot plasma core and the confinement time can depend strongly on this boundary condition. Examples are the observed transitions from the high confinement regime (H-mode of operation) to the low confinement regime (L-mode) in tokamaks which depend on the conditions in the edge plasma. In this context one can also expect the dust in the edge plasma to influence the global confinement time.

An amazing phenomenon observed in tokamaks is the so-called profile consistency — all tokamaks radial density profiles, when superimposed on each other for a proper choice of radial variables, coincide with each other. Any local change in the plasma distribution is related to the global plasma distribution — thus the change in plasma behavior close to the wall influences the global plasma profiles. The most developed explanation of the observed universal plasma profiles — the profile consistency — is found in Ref. [7]. Tokamaks, according to Ref. [7], are self-organized systems where the confinement is changed globally and the local disturbances are cured by the appearance of stochastic layers of random magnetic fields. The concept of self-organization in CTD has a long history starting with Taylor's proposal to explain the first British experiment ZETA. At the present time the principle of self-organization is widely used in many branches of physics and a review of it can be found in Ref. [8]. From these considerations it is clear that the self-organization processes are global and determine the properties of physical objects as a whole. Again, according to this point of view it can not be excluded that the change in tokamak edge plasmas introduced by the presence of dust can change the global confinement in the system.

Another physical and technical problem which may be related to the presence of dust in an edge plasma is the necessity to avoid local focusing of the heat flux on particular parts of the wall — a process which can be dangerous for the survival of the wall. Thus it is desirable to change the plasma properties close to the wall to be more turbulent. The presence of dust can help to make the system highly dissipative and to drive negative energy drift modes. The dissipation introduced by dust is related to dust charging which leads to a high rate of collisions of plasma particles with dust particles (in optimum conditions when the number of dust particles is sufficient to influence the conditions of quasi-neutrality the dust can increase the collision frequency Z_d fold or by $4-5$ orders of magnitude). This problem was discussed in Refs [9, 10] where it was proved that the presence of dust can decrease the threshold and increase the growth rate of drift waves, thus increasing the level of plasma turbulence close to the walls. This effect is desirable for the homogeneity of the heat flux onto the wall surface.

It has also been proposed to have a rain of drops or a rain of dust particles injected close to the wall to imitate a removable wall which will have less flux loading than the usual first wall [11].

Direct measurements of the dust distribution close to the walls have not been made up to now. In present tokamaks there are no appropriate windows close to the walls. The usual method for detection of dust particles is Mie scattering by laser radiation. This method has not been used in tokamaks for many reasons including that mentioned. Only recently laser light scattering of dust deliberately put into that part of running tokamak discharges where the scattering experiment can be easily performed has been described [12]. In general, performing the laser scattering experiment on dust close to the walls is a rather complicated.

Another diagnostic possibility is the use of collective scattering of relatively large wavelength electromagnetic waves [13] which occurs on the electron Debye shielding cloud of dust particles. The wavelength of the waves should be larger than the Debye shielding length to be sufficiently effective. This scattering can be called collective scattering since it is due to collective effects of plasma shielding of the dust particle field. However the collective scattering on dust in the sheath is more complicated than in a homogeneous plasma (the case considered theoretically in detail in Ref. [14]) since the thickness of the sheath is several Debye radii and the screening by electrons will be very inhomogeneous. The absence of a proper theory of the sheath which obviously can also be very turbulent and the absence of a theory of collective scattering for such conditions add to the difficulties of separating the scattered signal from the original one for forward scattering.

Surface erosion in CTD, well measured after discharges, is also indirect evidence of the complex processes going on at the surfaces including dust ejection.

Note that for more complete diagnostics it is desirable to know in detail the radial dust density distribution close to the walls and the distribution of dust particles according to size and charge as well as to other dust properties.

In the present design of CTD the role of dust is mainly ignored. Presently two disciplines are involved in the investigation of plasma – wall interactions: (i) *plasma and atomic physics* dealing with interaction of the plasma with the walls via the injection of neutrals, their ionization on the path to the hotter and denser plasma, charge exchange interactions, creation of impurities, diffusion in the edge plasma and (ii) *material science* dealing with the properties of different materials exposed to large heat and particle flux (melting and evaporation of the surface etc.). It becomes more and more clear that another branch of science — *dusty plasma physics* — should be included in the investigation of the regions between the walls and partially ionized plasma. In this region the dust can be responsible for part of the plasma – wall interaction and can change the plasma properties substantially. The problem is not only in the change of the transport near the wall but also in the change of the sheath structure, impurity generation and global confinement.

Thus one can say that the previous consideration dealing only with plasma and atomic physics, and material science, is probably appropriate only for low power wall loading. High power loading is expected in the new generation of tokamaks such as ITER or during disruptions in present tokamaks. In the case of high power loading a larger layer of dust is expected between the wall and the partially ionized plasma where the appropriate treatment can be made only with the help of modern dusty plasma physics. Dusty plasma physics is a rapidly growing branch of science with many new discoveries made recently including the new physics of dust – dust interactions in plasmas [14]. One can foresee that the future of CTD research with high power loading and long operation times needs this branch of science to be deeply involved and the problems arising to be thoroughly investigated.

We then summarize the results already understood in present CTD and will go on to describe the results of recent experimental data proving the dust agglomeration in the existing CTD.

Firstly, the present state of the art of the problem (adding some remarks):

1. Macro-particles can play an important role in fusion devices. Although their existence has been known for a long time, the possible consequences for plasma operation and plasma performance have been addressed only recently [4, 10, 12].

2. Dust particles are usually found near the bottom of fusion devices after some period of operation.

3. Dust particles are regarded as an important safety issue for ITER [6, 15] and future fusion reactors due to the large tritium retention and due to their very high reactivity in case of vacuum or coolant leaks.

4. It is highly probable that particulates from the previous history of plasma operation of a device may be reinjected into the plasma discharge and give rise to dust accumulation in the plasma edge. This may trigger disruptions and affect the boundary conditions for the density and temperature profiles and thus impact on plasma performance.

5. If one assumes that a highly dissipative dust layer is created between the plasma and the wall it can serve as a barrier to spread out the heat flux [9, 10] due to the enhancement of dissipative drift instabilities.

6. Important mechanisms for dust formation are evaporation and sublimation of thermally overloaded wall material, e.g. in the course of a disruption. Another generation mechanism is spoliation and the covering of thin films of redeposited material or of films grown intentionally for wall conditioning purposes [16]. Unipolar arcs can liberate droplets of molten metal. In addition to these ‘passive’ mechanisms, plasma induced *in situ* growth of particulates in the plasma edge from atomic or molecular precursors is probable. This mechanism will be of particular importance for long pulse devices. The initiation of the growth occurs via sputtered atoms or from the seeding of the edge plasma with hydrocarbons from chemical erosion of graphite wall components and of wall conditioning films of carbon, boron, or silicon [5, 16]. Under the conditions of a detached limiter plasma with a significant fraction of neutrals one obtains a local concentration of about 5 – 10% of methane near the wall assuming an effective chemical erosion yield of 1 – 2% and taking into account that the hydrocarbons are released with thermal velocities from the surface into the plasma. With the exception of a somewhat higher n_e, these conditions are close to those of process plasmas in which formation of particles has been observed [1].

7. Due to the topology of the edge plasma, negative particles formed by electron attachment will be well confined. The sheath potential in front of the limiters repels them and prevents them from reaching the surfaces, the magnetic field confines them in the radial direction, the Larmor radii being small due to their small velocity .

8. Unfortunately, no systematic *in situ* observations of dust particles in the plasma edge have been made so far. For calculations and constructing models of the dust layer it is not only crucial to know their density but also their distribution in size and velocity.

3. Problems to be solved

The main future problems concerning the presence of dust in edge tokamak plasma can be formulated as:

1. Can the existence of a dust layer in the edge plasma, in fact, be proved experimentally?

2. For which critical loading power can a dust layer appear?

3. What is the balance of dust growth, evaporation and agglomeration in edge plasmas, and is the formation of equilibrium dust layers possible where the dust generated close to the walls penetrates the volume and evaporates on the hot side of the layer?

4. Can the balance of dust particles be stable, and under which conditions is continuous growth of dust particles possible over the whole time of the discharge?

5. What is the possible thickness of the dust layer and what is its dependence on the level of turbulence?

6. Which part of the dust formed in previous discharges and disruptions can be reinjected into the plasma for the next discharge?

7. Can the accumulated dust to some rate trigger a new disruption?

8. Since a tokamak plasma is believed to be a self-organized system with profile consistency, can the L – H transition, related to the boundary edge plasma properties, be influenced to some extent by the dust accumulated in the edge plasma?

9. What kind of diagnostics of dust distributions by size is the best to use in an edge plasma?

10. How can the presence of dust change plasma transport properties and impurity generation?

11. What kind of regular coherent dust structures can be formed in an edge plasma and what is the relation of these dust structures with the coherent structures already observed in edge tokamak plasmas?

12. What is the role of tritium accumulated on dust particles as a safety issue for future fusion reactors?

These are questions for future research.

4. Dust agglomeration

We now describe recent achievements in understanding the agglomeration of dust particles in the plasma. This point is important for explaining recent experiments on dust detection in CTD, and it is important as well to draw the conclusion from these experiments that the dust in CTD exists in the plasma volume (is embedded in the plasma) and forms some kind of dust sheath in the edge plasma.

The agglomeration of dust particles is described as a merging of dust particles, forming larger dust particles. It occurs in most etching devices. Of course, this process can be understood as a process of dust attraction due to surface molecular processes if the dust particles have no charges. But the observed phenomenon is puzzling. The etching observations show that the dust particles continuously grow during the process of etching. Since in a plasma the charge of the dust particle is proportional to its size, the growing dust particles will continuously increase their charges and thus also the repulsive Coulomb forces proportional to the square of the dust charge Z_d. The Coulomb repulsion should prevent agglomeration. Something different is observed. The agglomeration occurs in two stages and the growth of dust occurs in three stages.

The first stage, of agglomeration observed in Ref. [2], seems to support the statement that the dust particles will agglomerate until the charges become sufficient for Coulomb repulsion preventing further agglomeration.

After that phase is finished the dust particles continue to grow by deposition of the plasma material on their surfaces. In this second stage no agglomeration occurs. It is interesting that dust particles of any shape with these sizes being injected into plasma soon become almost completely spherical in shape. This is an indication that dust particles of these sizes are growing due to material deposition from the plasma. The formation of almost spherical dust shapes is possible only when the dust is inside the plasma since only in this case the flux of deposit material will be isotropic. Thus if one observes dust of completely spherical shape, it indicates that these dust particles have been embedded in the plasma for a long time, so that the deposition of plasma material on the dust particles was indeed effective.

After this second stage of dust particle growth, when the size of dust particles reaches a critical value, a new stage of agglomeration starts by forming dust particles of cauliflower shape [1 – 3]. In experiments on etching this critical size is of the order of 10 – 100 μm while the first stage of agglomeration finishes at sizes of the order of 0.01 – 0.1 μm. The presence of cauliflower shape dust particles is also an indication that the dust particles were embedded in plasma for a long time, even longer than for formation of spherical dust particles.

This second stage of agglomeration was explained only recently [17] as the stage where the thermophoretic attraction forces overcome the Coulomb repulsion forces. These attraction forces are also inversely proportional to the square of the inter-dust-particle distance, as the Coulomb repulsion force, and depend on the density of the neutral gas component [17, 18]. They are attractive for dust surface temperatures less than the temperature of the neutral component. The physics of these forces is the formation of a temperature drop surrounding the dust particle which acts on another dust particle by attracting it to the region of lower temperatures through thermophoretic forces. The attraction force is proportional to the size of the dust particle to the fourth power ($\propto a^4$). It is also proportional to the neutral gas pressure ($n_n T_n$) and to the difference of dust and neutral particle temperatures. The dust particles are cooler than the surrounding neutral gas (and thus create an attraction force between them) when they are heated by neutral particle bombardment and cooled by radiation losses. The heat balance establishes the difference between the dust and neutral temperatures. This effect leads to saturation of forces with increasing neutral density. For small neutral densities the difference of the temperatures does not depend on the neutral density and thus the attraction forces increase linearly with increasing neutral density (i.e. with pressure increase). For neutral densities larger than a certain critical neutral density n_{cr} the temperature difference becomes inversely proportional to the neutral density, and thus the force becomes independent of the neutral density when it increases. The attraction force F_a is estimated as [18]

$$F_a \approx c \frac{a^4}{r^2} T_n n_n , \qquad (1)$$

if $n_n \ll n_{cr}$ and if $n_n \gg n_{cr}$ by substituting in Eqn (1) n_{cr} for n_n; $c \sim 1$. Here

$$n_{cr} = \mu\sigma \sqrt{\frac{\pi}{2}\, m_n T_n^5} , \qquad (2)$$

with $\sigma = 3.9 \times 10^{19}$ $cm^{-3}(K)^{-5/2} g{-}1/2$ and μ being the coefficient of grayness of a dust particle (the coefficient in the Stephan – Boltzman law for the dust particle emission rate) also of the order of 1.

We gave these results since we wanted to explain in physical terms the possible mechanism of dust agglomeration, and to estimate this process for the recent data of the TEXTOR-94 tokamak experiment showing the presence of dust agglomerates in CTD.

We should also mention how to estimate the value of dust charges which can prevent agglomeration. They are estimated from the condition that the dust potential is a floating potential or, more exactly, that the difference between the potential of dust particles and the bulk plasma is of the order of the electron plasma temperature. This condition can be expressed through the dimensionless dust charge z where

$$z = \frac{Z_d^2 e^2}{a T_e} . \qquad (3)$$

The estimate mentioned means that z should be of the order of 1. This estimate is valid for charging the dust particles negatively by plasma currents, in absence of UV radiation (which can charge the dust particle positively due to the photoelectric effect).

The physical explanation of the second stage of the observed dust agglomeration in etching experiments is obvious from the given formulas. The Coulomb repulsion force is proportional to a^2 while the attraction force (1) is proportional to a^4 and for certain large sizes the attraction force will dominate. The condition of agglomeration then reads:

$$n_{\mathrm{n}} a^2 a_0 \frac{T_{\mathrm{n}}}{T_{\mathrm{e}} z^2} \geqslant 1 ; \qquad a_0 = \frac{e^2}{T_{\mathrm{e}}} \tag{4}$$

[for $n_{\mathrm{n}} > n_{\mathrm{cr}}$ one should substitute n_{cr} for n_{n} in Eqn (4)]. The critical size a_{cr} obtained from Eqn (4) for equality corresponds to that observed in most of the etching experiments.

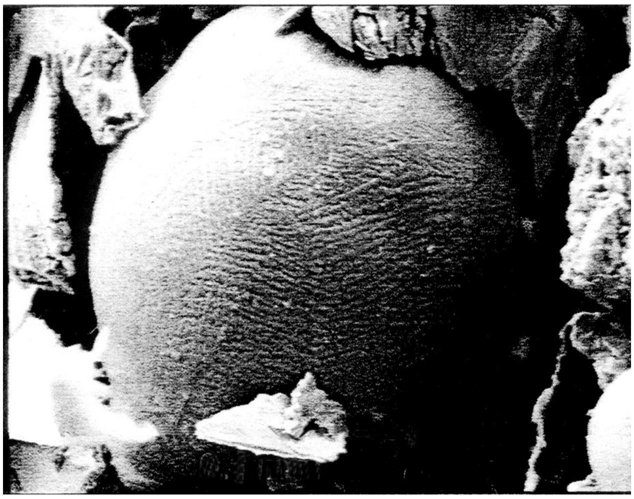
5. Recent experimental data on analyses of dust in controlled thermonuclear devices

Let us turn to the latest data of CTD experiments. The dust was collected from a TEXTOR-94 tokamak [19, 20] and analyzed in detail. The main result was that many dust particles found are almost completely spherical or of cauliflower shape which can only occur in the case when the dust was embedded in the edge plasma during the whole discharge and confined in the plasma as a dust sheath. It also indicates that the process of dust agglomeration was effective while the dust was inside the edge plasma.

First of all it is necessary to note that the edge plasma parameters in CTD make low dust charge agglomeration (first stage agglomeration) less probable and due to the rather high temperature of the hydrogen neutrals the agglomeration in CTD should correspond to the unsaturated second stage of agglomeration. The actual charge of the dust particles (either negative or positive) will depend on the intensity of the UV radiation field in the plasma edge which tends to photodetach electrons from the particles. For sufficiently high intensity UV radiation the electrons are emitted by dust particles via a photoelectric effect and the particles are charged positively (if the charging by photoelectric effect dominates over the charging by plasma currents). The criterion for agglomeration is independent of the sign of the charge since it depends on its square.

For the parameters given above the critical a value is $a_{\mathrm{cr}} > 10-20$ μm. The charging of particles of this size by plasma currents will give a charge Z_{d} which will be larger than 10^5. Dust particles with such large charges affect the plasma charge balance appreciably even if their densities are as low as $10^{-5} n_{\mathrm{e}}$ (because they have large charges). The dynamics of the edge plasma can then change significantly.

Supporting evidence for the mechanisms discussed above comes from a recent investigation of dust collected from the TEXTOR-94 tokamak [19, 20]. TEXTOR is a medium size device with a major radius $R_{\mathrm{major}} = 1.75$ m and a minor radius $R_{\mathrm{minor}} = 0.46$ m. TEXTOR has large area graphite limiters, and wall conditioning by plasma assisted deposition of boron films (boronization) is a standard procedure. The collected particles were investigated visually, magnetically and by Scanning Electron Microscopy (SEM). Their composition was investigated by Energy Dispersive Analysis of X-ray (EDAX) (see Fig. 1)†.



0.1 mm

Figure 1. An example of dust particle collected after operation of TEXTOR-94 [20]: the large iron sphere showing a regular surface texture.

The size distribution of the particles extends from the μm scale down to about 100 nm.

About 15–20% of the collected particles, including the smallest, are ferromagnetic although no magnetic materials are used for the construction of the wall components. Iron rich spheres with diameters of 0.1–0.01 μm were found in the magnetic fraction. They were possibly formed by arcing or agglomeration due to the surface tension of reheated evaporated metal layers on graphite surfaces. Their perfectly round shape may however also be due to repetitive interaction with the edge plasma (see above). The material most probably originates from the stainless steel wall components. Due to melting and resolidification and to the possible evaporation of some alloy constituents (Cr) they have lost the magnetic properties and resume a ferretic structure. Some spheres show domain structures with a typical length of the order of 30 μm and a width of 2–3 μm. Often magnetic constituents are flaked redeposited carbonaceous films with some metal inclusion. These carbon based flakes of redeposited material with ferromagnetic properties probably result from the co-deposition of carbon, boron and silicon low Z material with traces of metal impurities which are transported via the fusion plasma [15]. Chemical erosion of redeposited material will preferentially remove the carbonaceous matrix so that an enrichment of metals in the layer occurs. This process finally results in a high enough metal concentration to make the film magnetic. Magnetic particles are likely to be sucked into the magnetic field of the device and levitate on the high field side in an equatorial position (maximum of B). This will occur during ramping up the toroidal field before breakdown of the discharge. The presence of these particles may thus be the reason for the often observed problems during the start-up of tokamak discharges [20].

About 80% of the particles are non-magnetic, including thin flaked C/B/Si films, graphite crystallites and silicon particles created probably during injection experiments.

† This figure was added to the English version of the article by the author.

Many particles of sub-μm size exist, which themselves are agglomerates of 100 – 300 nm size particles. The shape of the latter is round and 'diffuse' and consistent with the cauliflower shape similar to that appearing in the plasma processing experiment [1].

The identification of these particles is taken as strong evidence for their *in situ* growth in the edge of the fusion plasma. Some of the larger particles on the 1 – 100 nm scale may then very well be due to the agglomeration processes discussed above.

6. Historical comment and conclusions

Historically the first investigation of the processes in edge plasma in CTD was made by V L Ginzburg [21]. The recent data indicate that not only the process considered by Ginzburg but the dust creation may be an important process in plasma – wall interaction. The observation of almost spherical shape dust particles as well as cauliflower shape dust particles collected after discharges in CTD is a strong evidence for their presence in the edge plasma volume during the discharges but still only indirectly. Experiments are under way to measure these particles by *in situ* light scattering. The presence of ferromagnetic dust particles also indicates that the plasma – wall interactions are indeed rather complex and need detailed investigation both for long operating times and high power loading.

Acknowledgements
One of the authors (V N Tsytovich) appreciates the discussion of the presented material during and after his lectures in Culham laboratory UK with C Larshmore-Davis, at the JET project with J Jacquinot and A Gibson, and in Australia University with S Hamberger and R Dewar. The authors appreciate the discussions during the Workshop on dusty plasma (Bad-Honnef, 10 – 15 January 1997) and the very useful comments of D Pfirsch, D Duchs and Y Elskens who read the manuscript before its publication.

References

1. Garscadden A et al. *Plasma Sources Sci. Technol.* **3** 239 (1994); *Proc. of NATO Advanced Research Workshop on Formation, Transport and Consequences of Particles in Plasmas* (Chateau de Bonas, Caster – Verduzan, France)
2. Boufendi L, Boushoule A *Plasma Sources Sci. Technol.* **3** 262 (1994)
3. Kamata N et al. *Plasma Sources Sci. Technol.* **3** 310 (1994)
4. Winter J "Dust in fusion plasmas" *Abstracts 170 WE Heraeus Seminar, Bad-Honnef, Germany, 15 – 17 Jan. 1997*
5. Winter J "Control of plasma surface interactions by thin films" in *Phys. Processes of the Interaction of Fusion Plasmas with Solids* (Eds W O Hofer, J Roth) (New York: Academic Press, 1996)
6. Piet S J et al. *Proc. 17 IEEE/NPSS Symp. Fusion Engineering* (San Diego, Oct., 1997)
7. Kadomtsev B B *Comments Plasma Phys. Controlled Fusion* **11** 153 (1987); **34** 1931 (1992)
8. Hasegava A *Adv. Phys.* **34** 1 (1985)
9. Benkadda S, Tsytovich V N, Verga A *Comments Plasma Phys. Controlled Fusion* **16** 307 (1995)
10. Benkadda S, Gabai P, Tsytovich V N, Verga A *Phys. Rev. E* **53** 2717 (1996)
11. Mirnov S M, Dem'yanenko V N, Murav'ev E F *J. Nucl. Mater.* **196 – 198** 45 (1992)
12. Naribara K et al. *Nucl. Fusion* **37** 1177 (1997)
13. Tsytovich V N , de Angelis U, Bingham R *J. Plasma Phys.* **42** 429 (1989)
14. Tsytovich V N *Usp. Fiz. Nauk* **167** 57 (1997) [*Phys. Usp.* **40** 53 (1997)]
15. Weinhold P et al. *J. Nucl. Mater.* **176 – 177** 150 (1990)
16. Winter J *Plasma Phys. Controlled Fusion* **38** 1 (1996)
17. Tsytovich V N, Khodataev Ya K, Morfill G, Winter J *Comments Plasma Phys. Controlled Fusion* **18** 321 (1997)
18. Khodataev Ya K, Morfill G, Tsytovich V N *J. Plasma Phys.* **50** 322 (1997)
19. Winter J *Proc. 24. EPS Conf. on Controlled Fusion and Plasma Phys., 9 – 13 June 1997* (Berchtegaden, Germany); *Plasma Phys. Controlled Fusion* (submitted)
20. Winter I, Gebauer G "Dust in magnetic confinement fusion devices and its impact on plasma operation" *Proc. 13th PSI, 18 – 23 May 1998, San Diego* (to be published in *J. Nucl. Materials*)
21. Ginzburg V L *Trudy FIAN* **18** 55 (1962)