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Dust limit management strategy in tokamaks

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ABSTRACT

Dust is produced in tokamaks by the interaction between the plasma and the plasma facing components. Dust has not yet been of a major concern in existing tokamaks mainly because the quantity is small and these devices are not nuclear facilities. However, in ITER and in future reactors, it will represent operational and potential safety issues. From a safety point of view, in order to control the potential dust hazard, the current ITER strategy is based on a defense in depth approach designed to provide reliable confinement systems, to avoid failures, and to measure and minimise the dust inventory. In addition, R&D is put in place for optimisation of the proposed methods, such as improvement of measurement, dust cleaning and the reduction of dust production. The aim of this paper is to present the approach for the control of the dust inventory, relying on the monitoring of envelope values and the development of removal techniques already developed in the existing tokamaks or plasma dedicated devices or which will need further research and development in order to be integrated in ITER.

1. Introduction

Particles and dust are produced in tokamaks by the interaction of the plasma with in vessel plasma facing components such as the first wall materials, divertor, limiters. They are created by erosion during normal operation of physics plasmas experiments where such events as Edge Localised Modes, disruptions or arcing may take place and during tokamak conditioning [1]. Maintenance operation can also lead to the production of dust, by fracturing flakes or removing deposits.

Dust has not yet been of a major concern in existing tokamaks mainly because the quantity is small and these devices are not nuclear facilities. However, in ITER and in future reactors, it will represent operational and potential safety issues. In terms of operation, the issues would concern the plasma performance (in particular disruption occurrence) [2–4], effects on some diagnostics (in particular mirrors) and the plant availability if downtime is necessary for dust removal.

Concerning safety [5], the presence of dust could lead to a potential radiological source term in case of accidental release to the environment, the possibility of hydrogen generation due to the chemical reactions between metal and steam/water after an in-vessel coolant leak, the possible dust cloud explosion following air ingress (and with certain other conditions, e.g. mobilisation, ignition source) and a contribution to the in-vessel tritium inventory.

In ITER, in order to control the potential dust hazard, a defense in depth approach is used which is designed to provide reliable confinement systems, avoid failures, measure and minimise the dust inventory. One important element of this approach is to maintain the quantities of dust below the levels assumed in ITER safety analyses:

- 1 tonne of mobilizable dust in the vacuum vessel (VV) during D–D and D–T phases (driven by the dust radioactive content).
- 6 kg of Be and 6 kg of C on the hot surfaces (driven by the chemical reactivity – complete metal/steam reaction for temperature above 400 °C for Be or 600 °C for C), or, if a design without C is selected, 11 kg of Be and 230 kg of W.

The administrative guidelines will have to take into account the accumulated errors on measurements and removal (Fig. 1).

The aim of this paper is thus to present a global approach, based on dust measurement and recovery, to make sure that the values are not exceeded.

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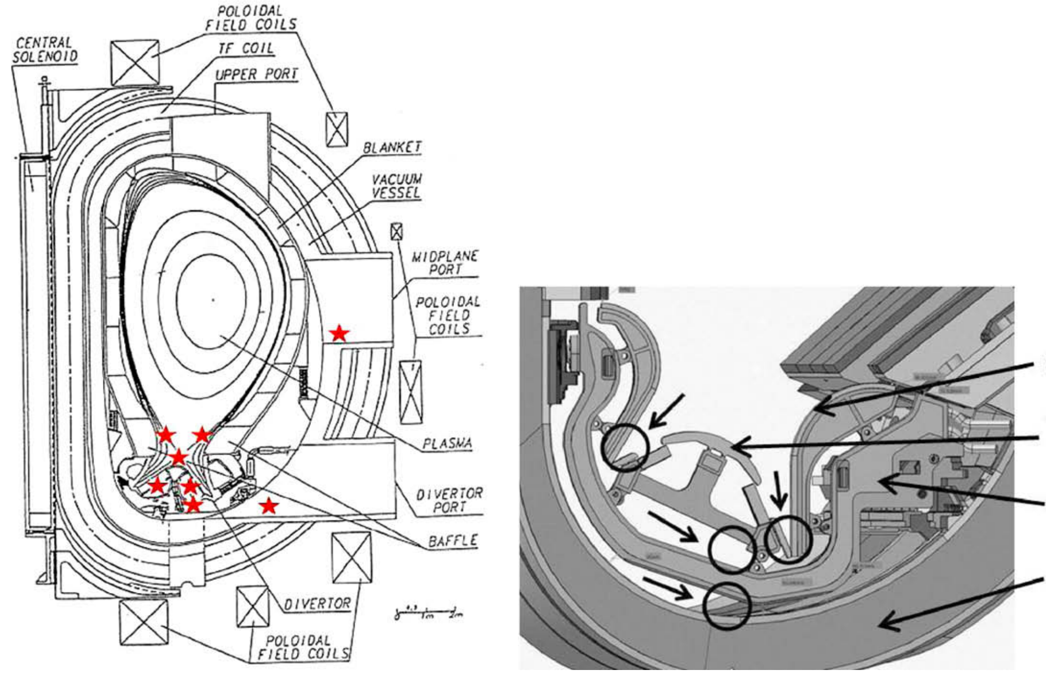

Fig. 1. Expected accumulation areas in ITER (stars and circles). (a) Divertor tile, (b) dome, (c) divertor cassette and (d) vacuum vessel.

2. Dust measurements

The experience from other tokamaks shows that dust will tend to accumulate mainly in the divertor region and in particular in ITER, under the dome and under the divertor cassettes. A small part of the dust is also expected behind the blanket tiles and at the horizontal ports.

2.1. Erosion source

The monitoring of the dust [6] in these recessed areas will be extremely difficult. For ITER, it is thus proposed to couple the measurement of the erosion source as a global envelope assessment and some local erosion and dust measurements. In order to determine the level of accuracy needed, a simple calculation shows that a homogeneous erosion of about 250 μm of an assumed full W divertor would lead to a tonne of eroded materials. It has to be noticed that the erosion will probably involve a much smaller area and then larger eroded thicknesses will contribute to reach the tonne of eroded materials. Erosion source during plasma can be assessed by spectroscopic measurements providing that the plasma edge conditions (ne, Te), and the relevant atomic physics (multiple excitation and ionisation rates) are known. Such measurements cannot characterize the erosion following ELMs or disruptions, due to poor acquisition time resolution, and will be much more complicated in the divertor region, mainly because of the requirements on the knowledge of the plasma edge conditions. Consequently, the laser in vessel viewing and ranging system (IVVS) based on amplitude modulated laser radar [7] could be used to determine the erosion patterns in between plasmas. In this case sub-millimetre resolution has been obtained so far in ENEA laboratory when the incident angle and the viewing distance were optimal: incidence at 0–45° for the first wall panels and only near 0° for the divertor tiles, target distance at 3.7 m in both cases. In ITER the use of 6 systems is currently foreseen to cover the major part of the divertor and the first wall panels. In addition, other techniques with higher accuracy (10 μm or less) such as Speckle interferometry or confocal microscopy used on Tore Supra tiles [8] could be implemented to obtain more precise measurement in areas of interest where erosion takes place. Due to ITER design configuration, part of the divertor will be very difficult to characterize (due to glancing incidence) and specific divertor erosion diagnostics based on laser measurements from under the divertor dome should be assessed.

2.2. Dust conversion factor

It has been observed that eroded materials create deposited layers that can then flake or directly produce dust. Observations in existing tokamaks as Tore Supra have shown that around 15% of the erosion source can be collected as loose materials using a vacuum cleaner [9]. Such conversion factor could be determined during ITER lifetime by performing extensive dust collection for accountancy purpose at various stages of the experimental programme (H, D and DT phases). The use of a conversion factor to determine a more realistic mobilizable dust quantity envelope value will need to be carefully assessed since the flaking conditions such as mechanical and thermal stresses during operation, presence of humidity, etc., leading to millimetre but also micrometre scale particles, are not well defined.

2.3. Local measurements

In addition and in order to gain knowledge on the dust creation and transport processes, the erosion measurements could be coupled with local dust measurements and characterization by sampling. Regular dust sampling would enable extensive analyses outside the VV: chemical and radiochemical analyses (including tritium content), size repartition, specific surface areas, etc. as a function of the sampling areas and the experimental programme. Various criteria have to be considered for the selection of collection techniques: impact on the dust properties (composition, size repartition, etc.), impact on the substrate integrity (remaining pollution), collection of a large spectrum of sizes (from 10 to 100 nm to mm) and materials, impact on the analyses to be performed, etc. Sampling techniques in existing tokamaks consist of using vacuum collection systems including filters (ash-free nitrocellulose filters, basalt-fibre or glass-fibre filters [10]), adhesive tapes (conductive tapes used for scanning electron microscopy), viscous substances such as collodion, brush, moist cloth [11], etc. In machines such as ITER, because of the radiation environment, the dust sampling will have to be performed through remote handling (RH) tools, reducing thus the possible techniques to vacuum cleaner collection with a possible impact on the minimum size of the collected dust.

Other local dust monitors such as Capacitance Diaphragm Microbalance [12] or electrostatic detectors [13], which detect respectively dust and film or only dusts settling on a surface, could be installed in specific areas where dust is expected to accumulate. The link between the local measurements and the global dust inventory in the VV will be difficult to establish. Nevertheless, since these local diagnostics are providing data on a pulse by pulse basis, a link between the plasma scenario and the dust creation and/or mobilisation could be determined. This would enable to establish for each plasma operation scenario the amount of dust produced with the associated uncertainties and prepare adequate means for its limitation.

Other simple tool such as a cross located under the dome and that cannot be seen anymore when it is covered by dust could be used to determine the presence of dust layer [14].

It appears that no single diagnostic will allow the total dust inventory to be determined precisely. Instead, a set of integrated measurements of different types and location will be required.

Evolution of dust quantities on the hot surfaces is even more challenging because of the accuracy needed and the divertor design. Possible strategies include the measurement of the dust and deposits together and/or the local measurements of the reactivity of these surfaces with water vapour. Further, limitation of the maximum amount of air entering the VV in accident conditions has to be foreseen and assessed to limit explosions.

3. Dust removal

Dust has to be removed before the in-vessel dust and tritium limit inventory are reached or when the operation is disturbed (high disruption frequency, polluted diagnostics mirrors, etc.). The removal of deposited layers since they can contribute to the dust and tritium inventory can also be foreseen. The removal of dust, flakes and deposited films from the vessel is a three stage process comprising material mobilisation (unsticking materials from the surfaces including gaps/castellations), collection of the mobilised materials and transport within/outside the vessel. The techniques to be used need to be efficient on a large range of particles sizes (nanometre to millimetre or more) and materials (C, W, Be and metallic impurities).

In addition to the efficiency on dust removal, all the integration issues have to be considered in the selection of removal schemes: limitation of dust spreading (in particular to areas more constrained such as divertor hot surfaces or diagnostic optics), minimum impact on conditioning and more generally on machine availability, compatibility with PFC materials (no damage such as cracks to the bulk), tolerance to gamma radiation, ease of fluid recycling, etc. The interaction with sensitive systems (diagnostics, diagnostic mirrors, cryopumps, valves, shutters, detritiation system, etc.) has also to be carefully assessed, management of removed dust.

The most promising technique for removal of large quantities of dust is the cyclone vacuum cleaning [11]. This has been used extensively in existing tokamaks as JET. This technique requires machine venting from 10^{-2} Pa to atmospheric (in order to maintain a good suction efficiency) and the divertor cassette removal (to have access to remote areas under the divertor dome and between the vacuum vessel and the divertor cassette). This operation requires shutdown time (about 6 months for the removal of all the divertor cassettes) and reconditioning and has thus an impact on machine availability. Moreover, the recovered dust will have to be characterized (quantity, size, etc.) in laboratory after being removed from the vacuum vessel.

In addition to vacuum cleaning, the use of fluids (liquid or gas) appears as a global removal scheme that should also be studied since it does not require divertor cassette removal. Water appears to be a potential candidate. Water will be present in case of PFC water leak and issues linked to the dusty water management already need to be addressed. The exit route for the dust could be the safety drain pipes present at the lower ports. The main issues concern the loss of conditioning (about 1 month to recover) and the potential increase of flaking because of humidity (as observed during Tore Supra maintenance for example) but it has to be compared to the shutdown time needed for the divertor cassette removal.

Laser ablation or shockwaves can also be used for dust removal or to displace dust to areas with less safety constraints (areas far from the plasma and thus not concerned by the limits on the hot surfaces). This technique has the advantage that it can treat flat surfaces as well as castellations [15,16]. Because of the duration of such a process (about 1 m^2/h without considering RH tool deployment), local treatments or multiplication of the RH tools should be envisaged. In order to facilitate the collection process, dust mobilisation could be performed in a glow plasma. As a matter of fact, dusts are rapidly negatively charged in a low temperature and low density plasma like glow discharge. Charged particles can then be collected by electrodes. Some preliminary experiments have been performed in a DC glow discharge experimental device at CEA Cadarache. The discharge current and pressure were set respectively to 1 A and 1 Pa. Using a heated cathode, the plasma potential was maintained at 50 V DC with respect to the grounded walls. Negatively charged particles could be trapped as a modulated voltage 80+/−20 Volts (10 Hz) was applied to an additional anode. Hence particles with diameter around 10 μm stuck on the electrode or felt on a receptacle placed under the electrode. In case of use in a tokamak, means to regularly collect the particles from the electrodes and extract them from the VV will have to be integrated.

All these techniques rely on the use of a robot arm to carry the process: suction end effector, fluid injection, laser and electrostatic collection tools, etc. The deployment of the arm will require maintenance shutdown. The use of fixed devices in ITER could also be envisaged but has a non negligible impact on the in-vessel design and would have to sustain in-vessel harsh conditions.

Finally, the efficiency of the removal processes will have to be characterized in situ to re-adjust the dust in-vessel inventory after removal.

4. Conclusion

Dust could represent operational and potential safety issues in ITER and in future fusion reactors. Erosion source is proposed as an envelope value to be monitored to assess the total dust inventory in the VV. It is shown that the dust management strategy must also rely on removal techniques.

Application of these techniques for measuring and recovering dust on a machine of the scale and complexity of ITER is challenging. An accompanying R&D programme is on-going to validate the approach presented in this paper for controlling dust amount in vacuum vessel, to establish the measurement uncertainties, to optimize the procedures and to analyse their integration in the design.

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