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Micro-particles in ITER: A comprehensive review

C. Grisolia [a,*], S. Rosanvallon [a], Ph. Sharpe [b], J. Winter [c]

[a] Association Euratom/CEA, DRFC/SIPP, 13108 St. Paul lez Durance, France
[b] Idaho National Engineering and Environmental Laboratory, P.O. Box 1625 MS 3860, Idaho Falls, USA
[c] Institute of Experimental Physics II, Ruhr-University Bochum, D-44780 Bochum, Germany

ABSTRACT

In a fusion reactor like ITER, in-vessel materials are subjected to interactions with the plasma. One of the main consequences of these plasma-material interactions is the creation of co-deposited layers. Due to internal stresses, part of these layers can crack leading to micro particle creation. The purpose of the following paper is to review the Tokamak operation processes which lead to erosion and layer creation. Then, the proportion of these layers that is converted into micro-particles will be evaluated in the case of Tore Supra experiments and extrapolated for ITER. It is major importance to measure the ITER mobilizable dusts present in the Vacuum Vessel and compare the measured quantity with the safety limits. When approaching these limits, removal systems must be used in order to control the in-vessel dust inventory. In the second part of the paper, diagnostics and removal system under development will be presented.

1. Introduction

During Tokamak operation and due to high heat and particle fluxes, Plasma Facing Components (PFCs) are eroded and material is re-deposited. Mainly due to internal stresses, these re-deposited layers are fragile and breakable leading to micro particles creation. For ITER extrapolations, it is of major interest to know the proportion of these deposited materials able to be converted into mobilisable dust. In order to quantify this transfer process, a dust conversion factor (Cd) can be used. Cd is the ratio between the total quantity of in-vessel dust (Qd) over the total quantity of eroded material (Qe) produced during operation:

$$\mathrm{Cd} = \mathrm{Qd}/\mathrm{Qe}$$

Qd can be experimentally obtained by vacuum cleaning for example in this Cd evaluation, all the eroded materials are supposed to be deposited and then part of them turns to be converted into dust. The upper limit of the in-vessel dust quantity at any time could be obtained knowing the eroded quantity (thus, Cd = 1). However, this constraint could be released with a reduced Cd. In the following paper, an experimental estimation of Cd as well as the ITER extrapolation of dust production will be presented.

This value of Cd could be used during ITER operation in order to estimate the in situ dust inventory and compare this value to the safety limits [1]. However, on line assessment of Cd or of the mobilisable particles must be available. In the second part of this paper, some of possible diagnostics will be presented. Finally, dust removal strategy will be addressed in order to recover the in-vessel dust if approaching the foreseen safety limits.

2. Tokamak dust creation processes and Cd evaluation

Cd was assessed for a five months (1438 shots) Tore Supra operation period. The total in-vessel dust collected during this campaign was 31 g [2]. In order to evaluate global Tokamak erosion, all the erosion processes have to be reviewed and eroded quantity assessed:

- Erosion during normal operation. The eroded quantity results to the sputtering of the carbon material by the plasma out-flux which is equal to $\mathrm{Np}/\tau\mathrm{p}$ with $\tau\mathrm{p} = 300$ ms. Considering a carbon sputtering yield equal to 0.02, C eroded quantity is 27 g. However, if 50% to 80% of the eroded carbon is re-deposited locally and takes part afterwards to the ongoing erosion process [3], this value appears to be an upper value of the deposited layers. The eroded value could be as low as $27*0.2$–5.4 g.
- Erosion during off normal erosion processes as disruption.The contribution of disruptions is much more difficult to assess. The thermal content of the discharge is known (∼300 kJ) but the surface of the interacting zone is not addressed precisely. However, from experiments results and code evaluation presented by Hassanein [4], it appears that the eroded quantity (Mc) per disruption could be approximated by:

$$\mathrm{Mc(g)} = [(\mathrm{Eth} * 0.1)/\mathrm{Esub}] * 12(\mathrm{g})$$

where Eth is the plasma thermal energy before the disruption and Esub, the C sublimation enthalpy. Here, it is considered that

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* Corresponding author.
E-mail address: Christian.grisolia@cea.fr (C. Grisolia).

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the time duration of the disruption is so small that Eth is deposited on the PFCs surface and contributes to sublimation. With Tore Supra operating parameter, the eroded material per disruption Mc is 0.6 g. Considering a disruption frequency of 10–15% during the considered period, this leads to 80 to 120 g of PFCs erosion.

- Erosion during maintenance activities like conditioning.During Tore Supra helium Glow Discharges (He–GD) (3 A of Glow current, 300 V glow voltage), the net erosion is 1.8×10^{18} Carbon/s, considering a carbon sputtering yield of 9×10^{-2} at 300 eV. For 1 day of He-GD, 3 g of C are sputtered. During the five months of TS operation and with regular He-GD cleaning sequence, at least 50 g of C could have been eroded.

Several observations [5] have shown the influence of moisture on the evolution of carbon deposited layers as a function of time. Cracks appear leading to embrittlement of the deposited layers, flaking and thus to dust creation. However, it seems that it takes days to observe this layer destruction in Tokamak at room temperature.

The quantity of Carbon eroded in Tore Supra during this five months operation campaign is therefore composed of:

- 27 g eroded during normal operation (this is an upper value that could be reduced by a factor 5).
- 80–120 g eroded during disruption.
- 50 g eroded during HeGD.

Total eroded quantity is close to 200 g, the main erosion pathway being clearly disruptions.

For this Tore Supra campaign, Cd is thus equal to 15% which is close to the ITER retained value (10%). A value recently published by JT60U [6] is comparable: 7%. From ITER calculation and in the frame of the current design, 50 g of material are eroded [13] per shot leading to a dust production of 7.5 g.

In contrary to the campaign studied above, Tore Supra is now an all actively cooled carbon machine. During current operation campaign, He–GDs are not used at a so high frequency. As an example, during the last 2007 campaign for several tens of plasma pulses, no He–GDs were undertaken and no operation constraints were observed. It will be the case in the ITER machine and as a consequence the material erosion during conditioning will be reduced. Then, ELMs (in the case of ITER) and disruption could be the major source of erosion.

For Cd evaluation or for a direct comparison with the safety limits, the ITER in-vessel quantity of mobilizable dust (Qd) must be measured. In the following chapter, the in-vessel diagnostics able to weigh up Qd and currently available are reviewed.

3. In situ tokamak dust measurements

In order to assess the Cd conversion factor, PFC erosion diagnostics are needed. The most common technique used in current tokamak to assess Qe is code evaluation of the erosion using the plasma edge impurity diagnostics. This was used in particular in Tore Supra [3] and JET [7]. This technique is well suited for in-vessel wall erosion assessment. However it is much more difficult for divertor area due to difficulty to diagnose the impurity in the divertor region (line of sight and spectroscopic signals interpretation). For a more reliable measurement, net erosion techniques able to measure the PFCs depth evolution (providing that a reference surface is available) as speckle interferometry [8] or laser metrology could be used. These techniques, developed at the laboratory scale, must be integrated and tested in Fusion machine environment. The capability of deducing global measurements from local ones due to reduce measurement zone must be also addressed. It has to be stressed that erosion diagnostics [14] are the only one that could give the envelope value of the in-vessel dust quantity considering Cd = 1 and enable the comparison with the safety limits.

Several other diagnostics operating on a shot to shot basis are also under development. Electrostatic grids [9] and Capacitive Diaphragm microbalance could be installed in places where dusts are accumulating as under the divertor or under the ITER dome. This system relies again on homogeneity assessment and the link with local measurements and Qd is not obvious. Optical techniques could be also used. Laser extinction [10] is the simplest one since it is measuring the attenuation of the laser light intensity along its propagation in the dust cloud. However, the interpretation of the measured signal turns to be very challenging because of the heterogeneity (in size, composition, shape,...) of the micro particles supposed to be produced during ITER operation. Furthermore, this airborne dust measurement relies on the use of gas puffing to put the micro particles in suspension as it occurs during an air ingress. The link between the airborne dust measured and the dust mobilisable during accident sequences relies on complicated fluid codes that do not exist yet. However, optical system as laser extinction could be inserted on in-vessel inspection robot and thus available for global assessment independently of in-vessel inhomogeneity.

Finally, mobilisable dust can also be measured via Vacuum Cleaner recovery that can be introduced remotely and used during shutdown. This diagnostic system that could be also used for dust removal has already proven its efficiency [11]. It seems nevertheless that accessibility will be an issue as well as the link between dust recovered and the real quantity of dust that could be mobilised.

As for erosion the need of Tokamak (or scale one mock-up) integration and test is mandatory in order to assess these diagnostics capabilities and accuracy in realistic conditions.

As a conclusion, a set of system seems to be available to measure the in-vessel mobilisable dust. This value could be then compared with ITER safety limits. Approaching these values; removal tools must be used.

4. In-vessel micro particles removal techniques

Micro particles in-vessel removal relies on rather clear principles. It is first necessary to unstick the particles from the surface. Due to Van der Waals, the action force needed is inversely proportional to the size of the particle. Then particles are collected and removed from the vacuum vessel. Two techniques could be used in order to mobilise the dust: high pressure gas injection and laser matter interaction.

Gas has been proposed but it has never been tested with realistic micro particles and in tokamak topology. The gas inventory control and treatments must be part of the assessment of this collection technique and has also to be addressed. When the particles are unstuck and mobilised, Vacuum Cleaning suction is the easiest one and already tested in JET.

The laser mobilisation technique [12] could be useful to access rather small structure like castellation and for all the particle collection, independently of size. Experiments with laser have already been done and have demonstrated the high laser efficiency for removing dust from castellations.

Laser interaction produces, under vacuum, small and high speed particles and collection by sticking on retrievable embarked system could be preferable in order to avoid huge amount of gas collection and reprocessing. In order to facilitate the collection process, laser 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. The collection could also be enhanced by the tritium beta disintegration that will naturally charge the particles in ITER. At higher pressure, vacuum cleaning suction could be also possible as for gas injection.

Several others proposals as liquid vacuum vessel washing are also under assessment (choice of the fluid, efficiency, fluid reprocessing, etc). This technique must be tested in mock-up prior to any test in ITER.

To conclude, it seems that the dust removal procedure relies on sets of techniques already tested that need to be adapted to the ITER design. However and as for the dust diagnostics, Tokamak integration and test must be foreseen as soon as possible to check the reliability of the techniques proposed in a realistic environment.

5. Conclusion

In this paper, the dust conversion factor has been estimated in a current operating Tokamak. It is of the order of 10% which is close to the value retained in the ITER dust production evaluation. Using the procedure presented here, Cd is under estimation among several operating worldwide Tokamaks in order to address the consequences of different operating mode (influence of ELMs for example) and material configurations (metal and non metal) on the dust in-vessel quantity.

Several diagnostics and removal system have been presented above. It appears clearly that a set of techniques are available to assess and control the dust in-vessel inventory. However, there is an urgent need of an integrated demonstration that has to be planned in a Tokamak environment or in a scale one mock-up.

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