DETERMINATION OF FUEL RETENTION IN TOKAMAKS BY ACCELERATOR-BASED METHODS

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Nuclear fusion offers a potential future energy supply and is an area of worldwide research with this aim in mind. One such research effort is at the world's largest operating tokamak device based in UK, known as JET – Joint European Torus. JET consists of a 6 m diameter torus (doughnut) shaped vacuum vessel in which high temperature hydrogen plasma is confined by magnetic field to facilitate fusion of hydrogen isotopes, deuterium (D) and tritium (T), to release high energy 14 MeV neutrons.

The inside of the JET vacuum vessel is protected by wall tiles. In the extreme conditions the plasma interacts with the wall components and as a result components undergo erosion, material migration and deposition. This plasma wall interaction has an impact on operational lifetime of components and has the potential to generate dust which poses a safety risk in the event of accident scenarios. Plasma interaction with the wall materials also results in the retention of the hydrogen fuel, including the radionuclide tritium, which is regulated to ensure safe operation of fusion facilities. For these reasons an extensive programme to study materials removed from JET has been ongoing for more than three decades and have influenced decisions on upgrades to JET and the choice of wall materials for ITER, under construction in France. The use of accelerator-based techniques has played a major role in the materials analysis programme and results have advanced the understanding of erosion, material migration, deposition and fuel retention in tokomaks and provided benchmarking for modelling. To facilitate the analysis programme, regular retrieval of plasma-facing components (PFC) and erosion-deposition probes (EDP) is performed during in-vessel maintenance periods in JET. In the current configuration of JET, known as JET ITER-like Wall (JET-ILW) [1], three sets of PFCs and EDP have been removed in the period 2011-2016 following three experimental campaigns lasting 1 – 1.5 years each. The components removed have provided a representative set of specimens for ex-situ studies and – as a consequence – have allowed for a deep insight into material migration including fuel retention and dust generation. This comprised research on PFCs from the poloidal (upper to lower) cross-section of the machine; tungsten PFCs in the bottom of the machine (known as the divertor) and beryllium PFCs in the main chamber of the vessel. The overall aims were: (i) to obtain a comprehensive erosion-deposition pattern and fuel retention assessment before the planned D-T experimental campaigns in 2021 and 2023; (ii) to provide basis for the best-possible predictions for ITER regarding the melt damage of bulk Be and W tiles, tritium inventory and the modification of diagnostic test components. In this programme ion beam analysis facilities with capability for handling components containing tritium and beryllium were crucial in all these studies. Using IBA techniques, the retention of the predominant deuterium fuel and deposition of beryllium and carbon has been extensively studied using nuclear reaction analysis (NRA) with helium-3 ($^3He^+$) beam. Other deposited materials have been studied using proton (H^+) back scattering (PBS), proton induced x-ray emission (PIXE) and heavy ion elastic recoil detection with time-of-flight detection (HIERDA, TOF-ERDA).

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An example of fuel retention analysis on a JET component is shown in Fig. 1. Fig. 1(a) shows a castellated beryllium component from the JET main chamber inner wall guard limiter (IWGL) and Fig. 1(b) shows the deuterium deposition profiles measured using accelerator-based techniques following the three experimental campaigns of JET-ILW (ILW-1, ILW-2, ILW-3) and a profile on the tile exposed during all of them [2][3]. There are common features. Qualitatively and quantitatively all profiles are of the same character indicating: (i) the erosion zone in the central part of the limiters where the content of D atoms does not exceed $0.1\text{x}10^{18}$ cm^{-2}; (ii) deposition zones at the curved sides with the D concentration from co-deposition with eroded material reaches a maximum of $1.4\text{x}10^{18}$ cm^{-2}. Even those highest values of inventory are very low on this component both in absolute and relative terms when either extrapolated to tritium retention in 1:1 D-T operation (35 mg T m^{-2}) or compared to the situation in JET with carbon walls (JET-C) where fuel contents in some areas was over two orders of magnitude greater than in JET-ILW [4][5]. This type of analysis is repeated for all components retrieved from the machine and a global picture of material migration and fuel retention is constructed. From the global analysis the long-term retention in components is found to be 0.19% of fuel used in operations and the highest retention area is at the upper inner part of the divertor, accounting for 46% of fuel retained. Such global analysis can be used in estimating retention of tritium in JET during use of tritium in 100% tritium and D-T operations from 2021 to 2023 [6]. These results in turn can provide an assessment of tritium waste liability and also tritium inventory of components to inform the infrastructure requirements for handling in the case of future analysis by accelerator-based and other tritium sensitive techniques.

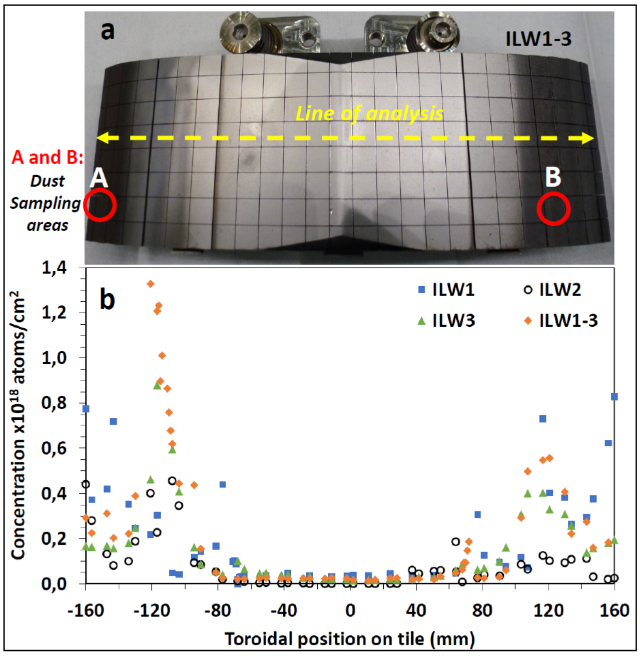

Fig. 1. (a) Castellated beryllium mid-plane IWGL tile after exposure in JET; (b) Deuterium areal concentrations at mid-plane measured after consecutive campaigns and after all three campaigns ILW1-3; data reproduced with permission of copyright holder UKAEA and author [2,3].

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