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Studies of dust from JET with the ITER-Like Wall: Composition and internal structure

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Results are presented for the dust survey performed at JET after the second experimental campaign with the ITER-Like Wall: 2013–2014. Samples were collected on adhesive stickers from several different positions in the divertor both on the tiles and on the divertor carrier. Brittle dust-forming deposits on test mirrors from the inner divertor wall were also studied. Comprehensive characterization accomplished by a wide range of high-resolution microscopy techniques, including focused ion beam, has led to the identification of several classes of particles: (i) beryllium flakes originating either from the Be coatings from the inner wall cladding or Be-rich mixed co-deposits resulting from material migration; (ii) beryllium droplets and splashes; (iii) tungsten and nickel-rich (from Inconel) droplets; (iv) mixed material layers with a various content of small (8–200 nm) W-Mo and Ni-based debris. A significant content of nitrogen from plasma edge cooling has been identified in all types of co-deposits. A comparison between particles collected after the first and second experimental campaign is also presented and discussed.

1. Introduction

Processes of dust generation and transport have been studied in present-day tokamaks for the last two decades. The main driving forces in research have been related to a whole spectrum of safety aspects and then licensing of a future reactor-class device, e.g. ITER. This has also included the assessment of deposition and dust formation on the reliability of in-vessel diagnostic components, especially metallic first mirrors. Therefore, detailed dust surveys have been carried out regularly in all medium- and small-size tokamaks and in several simulators of plasma-wall interaction (PWI). The bibliography of works performed until year 2010 is in [1], while results of recent examination in several machines are also available: TEXTOR [2,3], Tore Supra [2,4], ASDEX-Upgrade [5,6], FTU [7] and other machines.

Operation of JET with the ITER-Like Wall (JET-ILW) has brought a spectrum of new research aims and results connected to the new wall structure and composition: beryllium in the main chamber and tungsten in the divertor [8–9]. It has created new challenges related to the analysis of materials retrieved from the torus: marker tiles, wall probes [10,11] and dust. The aim in studying dust from JET-ILW is to provide a robust data base for the predition of dust generation in ITER, particularly categories and major formation mechanisms. Though JET-ILW has the best possible proximity to ITER, in PWI studies both similarities and differences in the structure of plasma-facing components (PFC) between two machines are thoroughly taken into account, e.g. solid Be and W components in ITER, while in some areas of JET-ILW tiles with either tungsten or beryllium coatings are used, as detailed in [8].

Dust retrieval was performed by vacuum cleaning during major in-vessel interventions (shut-downs) after two ILW campaigns from 22 out of 24 divertor modules: around 1.4 g after 2011–2012 and 1.8 g after 2013–2014 operation [12], thus corresponding to about $0.06\,g\,m^{-2}$ and $0.08\,g\,m^{-2}$ of the divertor surface area, respectively. When scaled to plasma operation time, these amounts were over two orders of magnitude smaller than those retrieved

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Table 1
List of studied materials with details on their origin and sampling location given in terms of the S-coordinate.

Tile / Sample	Region	Sampling location: S-coordinate (mm)
0	Outside deposition zone	110
0	Deposition zone	137
1	Apron (horizontal part of Tile 1)	210
3	Lower part below	590
6	Deposition zone in shadow of Tile 7	1415
Under tile 6	Divertor carrier	n/a
Mirror 119	Inner divertor, first mirror in the cassette	n/a

after the 2007–2009 campaign in JET with the carbon wall (JET-C) [13]. Besides vacuum cleaning, after the first ILW campaign dust, was also sampled by a carbon sticker from a single location in the inner divertor [14]. A widespread collection was performed after the second campaign.

This paper is focused on detailed studies of material sampled from many points on the divertor tiles and on the test mirrors located in the main chamber. The main goal is to relate the morphology of dust from various locations with the overall deposition pattern and with the operation history. This also includes a comparison of internal structure of co-deposits from the inner divertor after the two campaigns in JET-ILW, in the following called ILW-1 and ILW-2. The emphasis is on particles relevant from the ITER point of view: Be-rich deposits and metal droplets, while debris from W-coated carbon fibre composite (W/CFC) tiles will be only briefly addressed, as not relevant because no such coatings are foreseen for a reactor-class machine.

2. Experimental

The study was carried out for samples collected on tiles from the divertor modules which were not vacuum cleaned after the 2013–2014 campaign. Two complete modules equipped with erosion-deposition diagnostics [10] were transferred from the torus to the Beryllium Handling Facility (BeHF). Dust sampling was done manually at several different positions using adhesive carbon pads of 2.54 cm (1 inch) in diameter. This method enables a direct correlation between the location and the type of dust particles. However, the procedure has one disadvantage: only the bottom part and some side surfaces of the collected matter can be examined by optical or scanning electron microscopy (SEM), because the top layer is embedded in the glue of a pad. This problem is partly overcome by using focused ion beam (FIB) technique to obtain cross-sections of particles, but even this approach still prevents direct studies of the top layers. It is also limited to objects not thicker than 20 µm; above that value the quality of results is degraded. The information on the sampling is detailed in Table 1, while the image in Fig. 1 shows the divertor poloidal cross-section.

Dust found under Tile 6 on the frame of the divertor carrier was collected by wiping with a swab and then the matter was transferred to a sticky pad. In addition, brittle and dust-forming co-deposits on a metallic test mirror (First Mirror Test, FMT [15,16]) was examined. The mirror was located in the inner divertor in the shadow of Tile 3. No special dust sampling was required in this case.

The composition, size, surface topography and internal features of dust and deposits were examined using a large set of electron and ion beam methods. The analyses performed at the Warsaw University of Technology comprised: SEM (Hitachi SU 8000) combined with energy-dispersive X-ray spectroscopy (EDX, Thermo Scientific Ultra Dry, type SDD enabling Be analysis), focused ion beam (FIB/SEM, Hitachi NB5000) and scanning transmission electron microscopy (STEM, Aberration Corrected Dedicated STEM Hitachi HD-2700). Depth profiling (Be, C, N, O, W) was determined by time-of-flight heavy ion elastic recoil detection analysis (ToF–ERDA) with a 36 MeV $^{127}I^{8+}$ beam. The method gives good depth resolution of a few nm and it is particularly suited for studying smooth surfaces, e.g. mirrors. The information depth is limited to a few hundreds of micrometers because of a low incidence angle (22°). Global fuel retention studies (i.e. deuterium content analysis) could not be performed on samples collected by sticky pads. Thermal desorption, for obvious reasons, is out of question. However, detailed information on fuel retention in deposits determined by ion beam analysis (IBA) can be found [12].

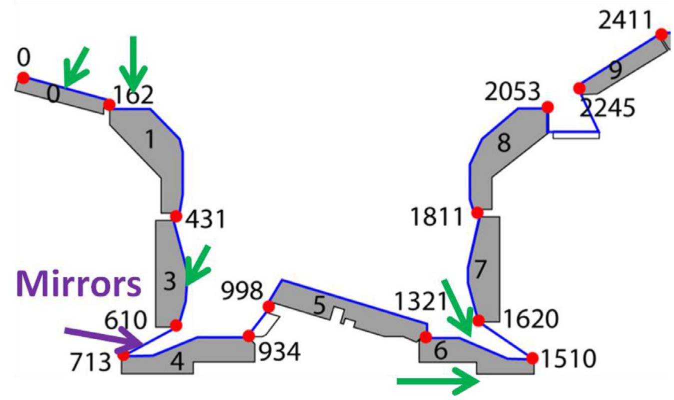

Fig. 1. Divertor poloidal cross-section in JET-ILW. Numbers correspond to S-coordinate denoting poloidal length in the divertor. Red dots mark edge point of respective tiles. Green arrows indicate positions of dust sampling, while the position of a cassette with mirrors in the inner divertor is marked with a violet arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

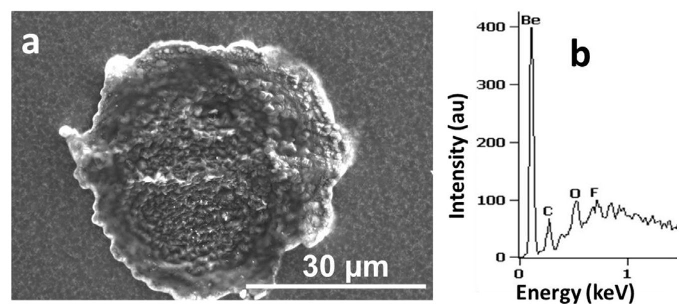

Fig. 2. (a) Beryllium flakes from the inner wall cladding on Tile 0 in the area without deposits, SEM SE image and (b) corresponding EDX spectrum.

3. Results and discussion

The presentation of dust survey follows the divertor poloidal cross-section starting from the inner divertor Tile 0 which acts as the High Field Gap Closure (HFGC) plate. A comparison of dust after the consecutive campaigns will be made for apron on Tile 1. The description of dust collected from plasma-facing surfaces will be complemented by the characterisation of particles taken from the divertor carrier below Tile 6. Finally, dust-forming deposits on the test mirror will be presented.

3.1. Dust on divertor tiles

Tile 0 has two distinct regions: shiny and “blackish” . A sample collected outside the “blackish” deposition zone is characterised by a small density of particles: thin though fairly large (dimensions from 30 µm to 300 µm) flakes rich in beryllium. It is documented by the image of a flake in Fig. 2(a). The corresponding X-ray spec-