EFDA–JET–CP(12)02/39

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

Preprint of Paper to be submitted for publication in Proceedings of the
20th International Conference on Plasma Surface Interactions , Eurogress, Aachen, Germany
21st May 2012 - 25th May 2012

ABSTRACT

This paper presents scientific and technical issues related to the development of erosiondeposition diagnostic tools for JET operated with the ITER-Like Wall: beryllium and tungsten marker tiles and several types of wall probes installed in the main chamber and in the divertor. Markers tiles are the standard limiter and divertor components additionally coated first with a thin sandwich of Ni-Be and Mo-W for, beryllium and tungsten markers, respectively. Both types of markers are embedded in regular arrays of limiter and divertor tiles. Coated W-Be probes are also inserted in the Be-covered inconel cladding tiles on the central column. Other types of erosion-deposition diagnostic tools are: rotating collectors, deposition traps, louver clips, quartz microbalance and mirrors for the First Mirror Test at JET for ITER. The specific role of these tools are discussed in detail.

1. INTRODUCTION

The Joint European Torus (JET) is the largest present-day tokamak. Its main scientific mission is to develop plasma operation scenarios for a reactor-class machine such as ITER. It is equally important to test the performance of Plasma-Facing Components (PFC). During over 25 years of operation the wall in the main chamber has been reconstructed several times and a number of divertor configurations have been tested [1-5]. JET is fully compatible with operation using deuterium-tritium mixture [6,7] and beryllium PFC [8,9], which are key features for the next-step fusion device. Until the year 2009 most PFC were made of Carbon Fibre Composites (CFC) but there were campaigns with beryllium limiter [10,11] and divertor [1,12] tiles. The wall was regularly coated with an evaporated beryllium layer [8]. The ITER-Like Wall (ILW) Project at JET was initiated to explore tokamak operation and plasma-wall interaction processes with the planned ITER wall material for the activated phase of the reactor: beryllium (Be) in the main chamber and tungsten (W) in the divertor [13-15]. The main driving forces for a large scale test of the metal wall are: (i) expected reduced retention of hydrogen isotopes in operation with a metal wall in comparison to carbon PFC; (ii) good plasma performance and gettering of oxygen impurities by beryllium; (iii) low erosion of tungsten at low ion temperature in the divertor. Operation with ILW has shown changes in the characteristic of Edge Localized Mode (ELMs) [16] and lower fuel inventory (gas balance) [17] in comparison to campaigns with carbon PFC [18].

Material erosion and fuel inventory studies are among top priorities. A large number of diagnostic tools has been developed and manufactured to elucidate the overall material migration scenario. They are based either on transport tracers or on deposition monitors. It is a continuation of the JET programme in Tritium Retention Studies (TRS) [19] but also new types of marker tiles have been introduced. The aim of this paper is to overview scientific and technical issues related to the development, manufacture and installation of markers and erosion-deposition probes.

2. CATEGORIES OF DIAGNOSTIC TOOLS

Two major categories of diagnostic tools have been developed and installed: (i) markers for studies of beryllium and tungsten erosion and (ii) active and passive deposition monitors. They are placed in many important locations in the torus in order to obtain a global and local pattern of material migration Detailed information regarding the types of probes, number of units and location in JET-ILW is given in Table 1. Deposition monitors are located either on divertor carriers or on wall brackets for installation on the main chamber wall. Markers, tiles and inserts, are placed in various poloidal and toroidal positions directly in PFC such as: (a) inner wall cladding, (b) tungsten-coated divertor tiles made of carbon fibre composites (W-CFC), (c) tungsten Load Bearing Septum Replacement Plate (W-LBSRP) [20] and (d) limiters: Outer Poloidal (OPL), Inner Wall Guard (IWGL) and upper dump plate. In most cases several diagnostic tools are installed on the same divertor carrier or in a given array of limiters. Their locations were near positions of other embedded diagnostics such as thermocouples and Langmuir probes. This methodology has had two important practical aspects. It allows for a meaningful overview of material migration by several methods and, a cost and time effective retrieval of Erosion-Deposition Probes (EDP) for ex-situ studies. All in-vessel operations of diagnostic removal/installation are performed by a remotely handled boom [15]. Inner and outer divertor carriers are equipped with a rotating collector, two Quartz MicroBalance (QMB) devices and two cassettes housing mirrors for the First Mirror Test in JET for ITER [21,22].

3. MARKERS

3.1 BERYLLIUM AND HIGH-Z MARKER TILES

To study beryllium erosion on limiters marker tiles have been developed. A marker is a regular beryllium tile coated first with a high-Z metal film acting as an interlayer and then with a Be layer of density similar to that of bulk beryllium. It is important to ensure good adherence and thermo-mechanical, and physical properties of the coating: best possible match of linear thermal expansion coefficients (α_{LTE}) and a melting point of the marker higher than that for beryllium, T_m(Be) = 1551 K. Nickel [T_m(Ni) = 1726 K] was selected as an interlayer (2-3μm) material to separate the bulk Be tile from a 7-10μm thick beryllium coating. The values of α_{LTE} for both metals are similar over a large range of temperatures, from about 12.5×10^{-6} K^{-1} and 15×10^{-6} K^{-1} at 447 K to 17×10^{-6} K^{-1} and 17.3×10^{-6} K^{-1} at 1073 K for Be and Ni, respectively. The films are obtained by the Thermionic Vacuum Arc (TVA) method [23] which allows for production of highdensity layers. In the development phase a series of marker coupons were produced and examined by several material analysis techniques before and after High-Heat Flux (HHF) testing with an electron beam in the JUDITH facility [24]. HHF screening tests allowed for the determination of the power and energy density limits deposited onto the surface at which damage to a marker occurred. A cyclic test served to assess the thermal fatigue under repetitive power loads. Uncoated Be blocks were tested for comparison. The major results may be summarised by the following: (i) the markers survived without noticeable damage at power loads of 4.5MW m^{-2} for 10s (energy density 45MJ m^{-2}) or for fifty repetitive pulses performed at 3.5MW m^{-2} each lasting 10s, i.e. corresponding to the total energy deposition of 1750MJ m^{-2}; (ii) in both cases the surface temperature measured with an infrared camera was around 873 K; (iii) damage to the Be coating occurred at power loads of 5MW m^{-2} for 10s. Plots in Fig.1 show depth profiles obtained by Secondary Ion Mass Spectrometry (SIMS) for two marker coupons: (a) unexposed to heat loads and (b) after HHF test carried out for 10 s at a power density of 4MW m^{-2}, i.e. total energy density of 40MJ m^{-2}. Both profiles are quite similar (Be coating thickness ~9.5μm) thus indicating that the applied power loads neither damage the coating nor cause intermixing of Be and Ni. There are some impurity species (Al, Si, Fe) but their content is below 1% as determined by ion beam analysis, energy and wavelength dispersive X-ray spectroscopy. Metallographic cross-section of the HHF tested coupon revealed a clear separation of beryllium and nickel thus proving durability of the coating. The manufacture procedure was qualified [25] and this was followed by deposition of Ni/Be coatings on 43 castellated blocks which were then embedded in segmented limiters. The location of marker tiles on the part of the inner wall limiters and cladding is shown in Fig.2.

3.2 BERYLLIUM COATINGS ON INCONEL AND WALL INSERTS

The inner wall cladding and the dump plate tile carriers are made of cast Inconel®. These tiles are in the shadow of bulk Be tiles, but to minimize the risk of high-Z impurity (Ni, Cr, Fe) influx, the Inconel is protected by about 8 μm thick evaporated Be coatings. During regular plasma operation in JET, the estimated power load to the cladding is 0.5-0.7MW m^{-2} for 10s corresponding to energy deposition of 5-7MJ m^{-2}. The R&D process which involved HHF testing indicated that the Be coating on Inconel would melt at energy loads exceeding 30MJ m^{-2} [25,26]. Such tiles themselves can serve as Be erosion markers in recessed areas, but even more precise tools for material migration studies are wall inserts, called also "sachets" [27] made of Inconel 600. These are metal "buttons" inserted in the cladding. The scheme of the sachet and assembled marker tiles are shown in Fig.3. The plasma-facing surface, 10 mm in diameter, is roughened in order to ensure the same roughness as the rest of the JET wall. One half of each sample surface was coated by nominally 40nm W using physical vapour deposition (evaporation) and the other half is covered by nominally 3μm Be. To draw conclusions regarding erosion-deposition on the inserts one has to determine the difference in composition and thickness of the marker layers (Be and W) before and after the exposure to plasma during the whole campaign. Therefore, the exact initial thickness was determined using ion beam analysis methods.

3.3 TUNGSTEN MARKERS

Markers tungsten migration studies are placed in the divertor, both on W-coated CFC blocks and in the W-LBSRP. These are standard tiles or lamellae respectively first coated with a molybdenum interlayer (3-4 or 6-7μm dependent on the location) and then with a tungsten film of the thickness of 4 or 5-6 or 12μm dependent on the location. The choice of Mo-W system is related to the similarity of crystallographic structures (both are bcc metals) and αLTE coefficients, 4–5×10^{-6} K^{-1}. This ensures mutual adhesion and thermo-mechanical integrity of the Mo-W layer under thermal excursions.

Though metals have high melting points, $T_m(Mo) = 2896$ K, $Tm(W) = 3695$ K, such shocks may lead to coating detachment from CFC because of α_{LTE} mismatch: below 1×10^{-6} K^{-1}. The other possible cause for marker destruction is inter-diffusion and W-Mo alloying at operation temperatures above 1700 K, thus making post exposure depth profiling with ion beam analysis inconclusive. The potential benefits for material migration studies overweigh the possible difficulties. The layers were obtained by means of combined magnetron sputtering and ion implantation (CMSII), i.e. the technique applied to coat CFC divertor tiles with tungsten [28,29]. Images in Fig.4 (a) and (b) show respectively a microstructure of the W-Mo layers and a W-LBSRP with marked positions of marker lamellae in the center and in a shadowed part of the stacks.

4. DEPOSITION MONITORS

EDP have been included in the TRS programme at JET campaigns for over ten years. Probes, active and passive, are installed in locations protected from direct plasma impact, i.e. deep into the scrape-off layer on the main chamber wall or in areas protected by the divertor tiles. Their role is to monitor material transport to various places in the machine. QMB devices are active monitors which have previously provided data after individual discharges [30]; e.g. to relate operation scenario with erosion-deposition processes [31]. Information from passive monitors is obtained by surface analysis techniques after an entire campaign when devices have been retrieved from the vacuum vessel during a major shut-down. For the use at JET-ILW a new set of EDP was installed after a design review and necessary modification of earlier monitors [19] in order to meet requirements of operation with metal walls.

The rotating collector is a diagnostic based on a drive mechanism powered by the magnetic field [19,32]. Every pulse for which the field coils are energised, will advance the first wheel in a gear chain by one step. A collector plate that can be easily removed for analysis fits on the final gear of the chain, and is exposed through a slot in the end of the case and/or in the cover plate. Erosion - deposition will be monitored during over ~3000 pulses with a time resolution of either 25 or 50 pulses (1 or 2mm slot width, respectively). Since the units need no electrical connections, they can be fitted to the outer vessel wall in addition to the divertor locations. A wall module includes a rotating collector and a mirror test unit [21]. One such module is placed near a Be evaporator, so the collector will collect the Be from that head for each evaporation. Provided there are at least 50 pulses between evaporations, then each evaporation will be separately monitored.

Passive diagnostic tools comprise divertor deposition monitors, louver clips and mirror test units. Clips are clamped on the water-cooled louvers in the shadowed region in the outer and inner divertor. The device consists of two jaws, Inconel probes fixed to the jaws and a spring. Divertor deposition monitors are “traps” for particles transported to remote regions [33]. Drawings in Fig.5 show schematically the shape and dimensions of the monitor. Cover plates of the traps for ILW are made of 316LN stainless steel whilst a graphite plates were used previously.

30 polycrystalline molybdenum mirrors (4 coated with 1 μm of Rh [34]) were installed in eight

cassettes located in the divertor (base, inner, outer), and two on the main chamber wall, as mentioned above [21]. The so-called “First Mirror Test”, is carried out for ITER because metallic mirrors will be essential components of all optical spectroscopy and imaging systems for plasma diagnosis in a reactor-class device. Optical and other surface properties of mirrors are characterized before and after exposure [22]. The cassettes housing mirrors under the lamellae of W-LBSRP were modified to fit the wedge [20] supporting the bulk tungsten structure.

CONCLUDING REMARKS

Best efforts have been taken to develop, test the performance and install tools for erosiondeposition studies in JET with ILW. For beryllium markers on limiters and coatings on the inner wall cladding the primary interest in R&D was on power handling capabilities and material purity. The results of material analysis before and after HHF testing indicate that coatings should withstand conditions of the regular JET operation without melting, exfoliation or phase transformation. This is particularly important in the case of the marker tiles for long-term Be erosion studies in the main chamber. Markers, active and passive deposition monitors will be retrieved for ex-situ examination during the shut-down. The ultimate goal in studies will be the correlation of data obtained by in-situ techniques (spectroscopy, thermocouples, Langmuir probes [35]) with surface measurements on the various erosion-deposition diagnostic tools.

ACKNOWLEDGEMENTS

This work, supported by the European Communities under the contract of Association between EURATOM/VR., was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The work was partly funded under the Contract 621-2009-4138 from the Swedish Research Council (VR).

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Category	Type	Location	Number of units
Marker	Be marker tile	Limiters: IWGL, OPL, upper dump plate	35
	W marker tiles	Divertor: bulk tungsten lamellae Divertor: W-coated CFC	11 12
	W & Be sachets	Inserts in inner wall cladding tiles	9
Active monitors	Quartz Microbalance Device	Inner divertor; 2 toroidal locations Outer divertor; 1 toroidal location Under W-LBSRP; 1 toroidal location	3 1 1
Passive monitors	Deposition traps	Divertor: inner, outer, W-LBSRP, 1 toroidal loc.	3
	Rotating collector	Divertor: inner, outer, W-LBSRP, 2 toroidal loc. Main chamber outer wall, 2 toroidal locations	3 2
	Louver clips	Divertor: inner, outer, 3 toroidal locations	5
	Cassettes with mirrors	Divertor, inner, outer, W-LBSRP, 2 toroidal loc. Main chamber outer wall, 2 toroidal locations	6 4

Table 1: Types and location of erosion-deposition probes installed in JET-ILW

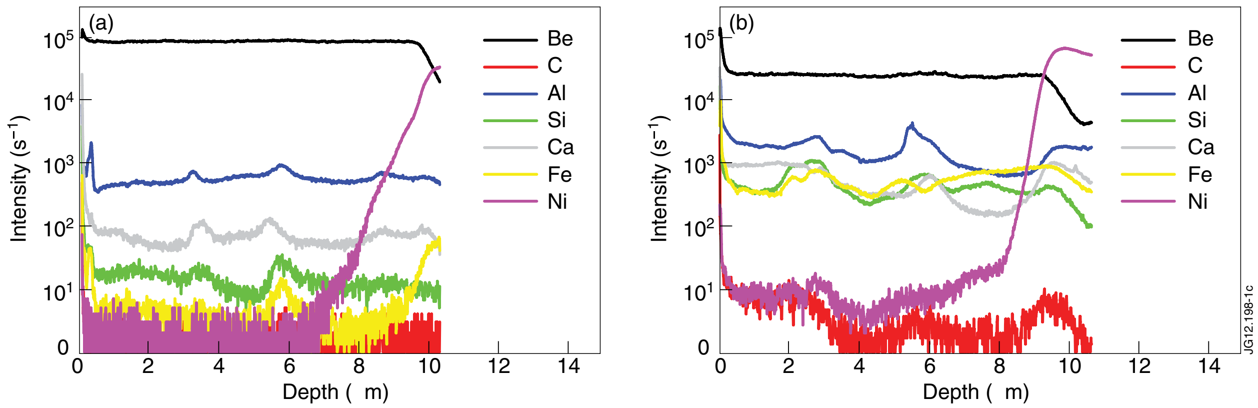

Figure 1: SIMS depth profiles for two markers: (a) "as produced"; (b) HHF tested at 40MJ m^{-2}.

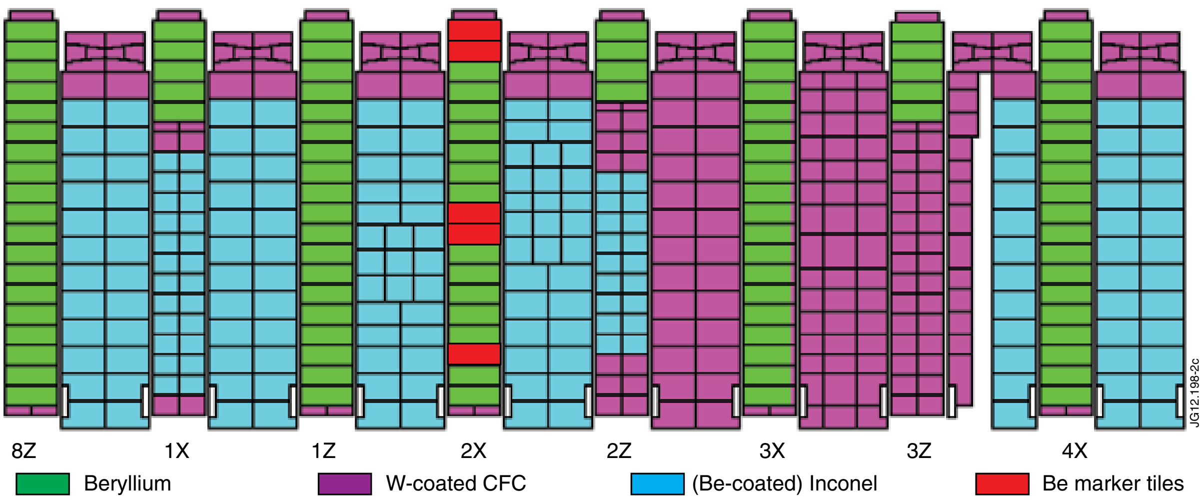

Figure 2: Location of different types of tiles, including Be markers, on the inner wall.

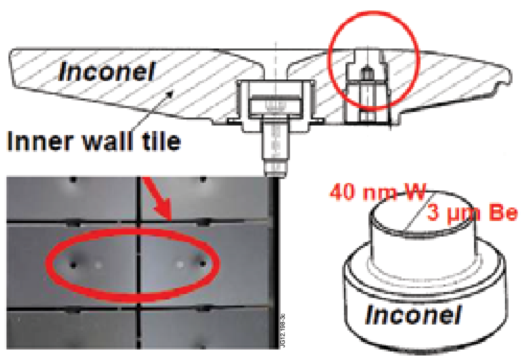

Figure 3: Inner wall cladding tile with sachets coated with marker layers.

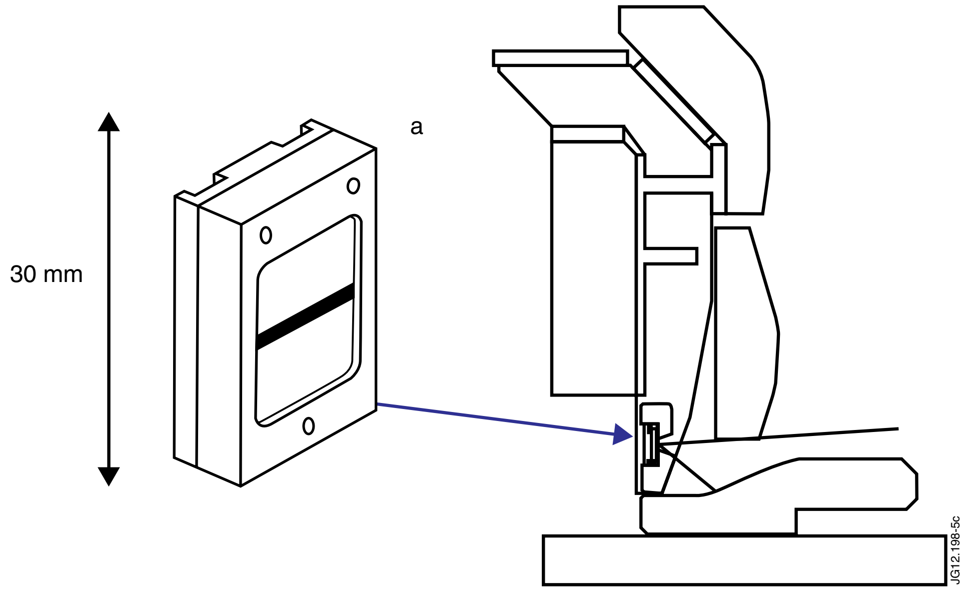

Figure 4: Mo-W markers: (a) structure of the coatings; (b) a W-LBSRP unit showing the banks of solid W lamellae, with the positions of the rows with markers.

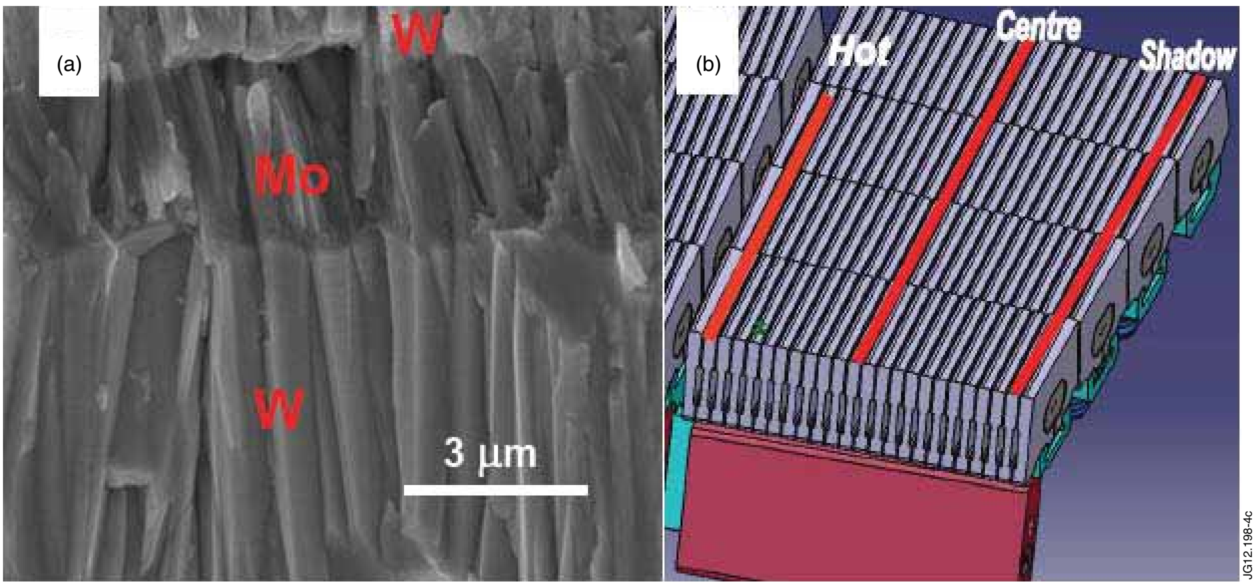

Figure 5: A deposition monitor.