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Microstructure and inhomogeneous fuel trapping at divertor surfaces in the JET tokamak

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ABSTRACT

The plasma deposited layers at divertor surfaces in the JET tokamak with carbon wall have been studied post mortem, using micro ion beam analysis (μ-IBA) methods, optical microscopy and scanning electron microscopy (SEM). The layers were formed during plasma operations over different periods through 1998–2009. They frequently have a columnar structure. For μ-IBA a 3 MeV ^{3}He beam was used, focused to about 5–15 μm size. Nuclear reaction analysis was used to measure D, Be and C. Elemental mapping was carried out both at the original surface and on polished layer cross sections. Trapped deuterium is predominantly found in remote areas on the horizontal bottom divertor tiles and in regions with locally enhanced deuterium concentration on the vertical tiles. Pockets with enhanced deuterium concentration are found in the carbon fibre composite (CFC) substrate. Areas with dimensions of about 100 μm with enhanced deuterium concentration are also found inside the deposited layers. The inhomogeneous fuel trapping is tentatively explained with co-deposition in partly protected pits in the substrate and by incorporation of dust particles in the growing layers.

1. Introduction

Materials migration in fusion plasma devices is a growing concern as research is moving on towards more reactor relevant, high duty cycle operation in large devices. The major issues related to materials migration are the life time of plasma facing components at surfaces with predominately erosion, the trapping of fuel (D and T) in deposited layers and dust production when thick deposited layers break up [1,2]. Additionally, if more than one material is used at plasma facing surfaces, the effects of materials mixing are a potential problem.

Over the last three decades, the surface conditions in JET and other large fusion devices have been very extensively studied post mortem. The main tools in these studies have been ion beam analysis methods (IBA) [3–5], optical microscopy [6], profilometry [7] and secondary ion mass spectrometry (SIMS) [6]. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) have also been employed [4,8–10]. Up to 2009, JET was operated with carbon (mostly carbon fibre composite, CFC) at the most plasma exposed surfaces. The recessed parts of the wall were made of Inconel and surfaces were periodically conditioned by depositing thin layers of beryllium [7]. Already more than 20 years ago it was demonstrated that large amounts of deuterium could be trapped by co-deposition with carbon at deposition dominated surfaces [11]. At divertor surfaces in JET, up to about 1 mm thick deposited carbonaceous layers have been formed [6,12,13]. The undesired fuel trapping in such layers has prompted efforts to develop methods for in situ removal of layers, or of their fuel content [15]. It has also pushed design efforts towards avoiding carbon as plasma facing material, in favor of beryllium and tungsten [1,16], which trap less fuel by co-deposition.

In recent years there has been an increasing attention to the microscopic inhomogeneities in fuel trapping [4,12,13,17–20]. Deuterium is frequently found trapped at higher concentration in determined sub-layers, parallel to the surface, which can

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[1] See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA.

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sometimes be related to the plasma operations history [12,13]. But the deuterium trapping is often also inhomogeneous on a microscopic scale in the directions parallel to the surface, with local regions trapping 2–80 times more deuterium than the surrounding areas [4,13,17–20]. It is clearly important to investigate such non-uniform fuel trapping: from the point of view of basic understanding of the deposition and trapping processes, in order to interpret surface analysis results correctly and to facilitate the development of efficient fuel removal techniques. This report aims at mapping the fuel trapping in deposited layers in JET with carbon wall and if possible at relating it to the physical structure of the layers.

2. Experimental

Fig. 1 shows a poloidal cross section of the inboard tiles of the JET divertor. Samples of the tile surfaces have been removed for analysis following every major period of JET operations since 1998: 1998–2001 (7278 plasma pulses with plasma current larger than 1 MA), 2002–2004 (6797 pulses), 2004–2007 (5182 pulses) and 2008–2009 (6937 pulses). The original surfaces and layer cross sections of one set of samples were studied with microscopy and with microbeam IBA (μ-IBA). Another set of samples was used to produce polished cross sections of the deposited layers, which could be studied microscopically and with μ-IBA. The cutting, polishing and optical microscopy was carried out at VTT in Otaniemi. Scanning electron microscopy (SEM) was made with a Zeiss Ultra 55 instrument at KTH, Stockholm. The microbeam set up at the Tandem laboratory in Uppsala and the quantification method for the nuclear reaction analysis are described in [17]. A beam of 3 MeV $^3He^+$ was used, the Be/C concentration ratio was determined from ratio of the ^9Be ($^3He,p_0$)^{11}B and ^{12}C ($^3He,p_0$)^{14}N proton yields, and the deuterium content from the D(^3He,p)^4He reaction. Calibration was made using thick elemental samples [17]. The data for Figs. 1 and 2 were collected with two circular detectors at interaction angle around 131° providing a solid angle of 0.1 sr [17], while for Fig. 4 an annular detector with interaction angle around 163° and 0.4 sr solid angle was used. In both cases the detectors had 1500 μm depletion layer to stop protons completely, and were covered with foils to stop backscattered ions. The need for background subtraction is discussed in [12,13]. The effects of sample preparation in the case of polished layer cross sections is discussed in [14], where it is shown that the measurements on polished surfaces underestimates the Be/C and D/C concentration ratios, either due to the surface being covered with a thin layer of epoxy, or because of selective removal, but that the effect is small if non-polar polishing liquid is used. The beam spot size was typically 5–15 μm. For calculating the local composition it is assumed that it is approximately constant over the accessible depth in the direction of the beam ~20 μm. The density of the deposited layers is assumed to be ~1 g/cm^3 [22].

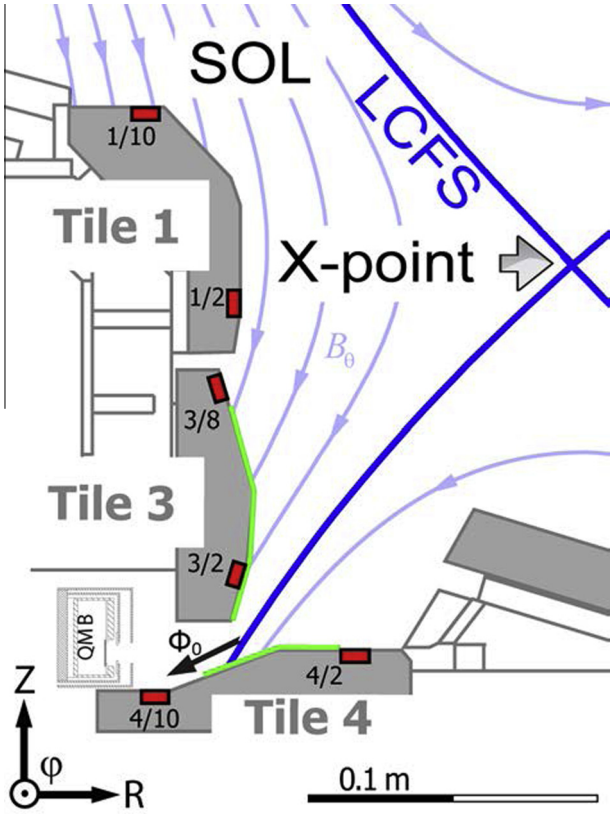

Fig. 1. Poloidal cross section of the inboard leg of the JET divertor. The numbered positions indicate where samples of the tile surfaces were taken. The regions for typical strike point positions on tiles 3 and 4 are shown in green. Ions are forced to move mainly along the magnetic field lines and cannot reach remote areas like 4/10, where the deposition has to be due to a flux of neutral species from the strike point region, approximately in the direction of the arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

Fig. 2a shows a region with locally enhanced deuterium retention at position 1/10, at the surface of a layer that was deposited in 2007–2009. This horizontal surface is exposed to the scrape-off layer (SOL) plasma. It has been shown previously that the layer is about 50 μm thick and is composed of 4–5 wide lamellar layers, which have internally columnar structure, with the projection of the column direction in the poloidal plane nearly normal to the surface [13]. The layer contains deuterium throughout, but with the highest concentration (D/C ≈ 0.2) at the interface with the CFC substrate [13]. The surface region with high deuterium content

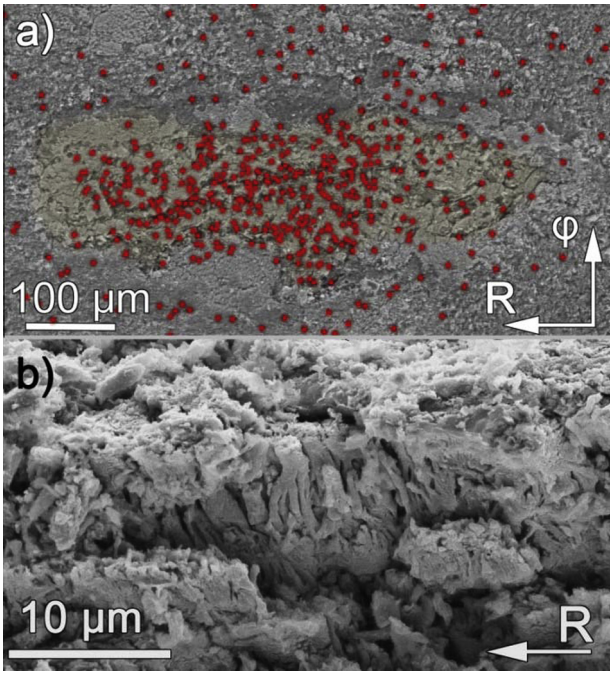

Fig. 2. Region with enhanced deuterium retention at the surface at position 1/10. The layer is about 60 μm thick and was deposited in 2007–2009. (a) Scatter plot overlaid on a SEM image, each dot represents a single proton count from the D(^{3}He,p)^{4}He reaction. (b) Close up of the D-rich region, viewed at an oblique angle.

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