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Characterisation of surface layers formed on plasma-facing components in controlled fusion devices: Role of heavy ion elastic recoil detection

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ABSTRACT

Wall components retrieved from the TEXTOR tokamak after tracer experiments with nitrogen-15 and molybdenum hexafluoride (MoF_6) injection were studied to determine deposition patterns and, by this, to conclude on material migration. Toroidal limiter tiles made of carbon fibre composites and fine grain graphite were examined using time-of-flight heavy ion elastic recoil detection analysis. Molybdenum deposition patterns indicated migration based on erosion and prompt re-deposition. Nitrogen-15 was trapped together with the deposited molybdenum. Some information on the depth distribution of species in the top 400 nm layer of the limiters was obtained; however surface roughness of the samples strongly limited resolution. In the case of molybdenum, the largest concentration was found in the 100 nm outermost layer, whereas fluorine and nitrogen-15 displayed more irregular profiles. Other species, besides deuterium fuel and carbon-12, were also identified: boron-10 and boron-11 originating from boronisations, carbon-13 from earlier tracer experiments, nitrogen-14 from plasma edge cooling and metals eroded from the Inconel wall.

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1. Introduction

Controlled fusion devices with magnetic confinement feature toroidal vacuum vessels that belong to the largest vacuum systems used in science and technology today. For example, the vessel volume is 100 m^3 in the Joint European Torus (JET) which is the largest present-day tokamak, while around 1600 m^3 is the design value for the International Experimental Thermonuclear Reactor (ITER) [1]. Consequently, the surface area of the plasma-facing wall is of the order of tens of square meters in smaller fusion devices, nearly 200 m^2 in JET and 850 m^2 is projected for ITER. The structure of the wall is highly complex. This is demonstrated in Fig. 1a, which shows a toroidal view into the vacuum vessel of TEXTOR, a medium-sized tokamak (volume 10 m^3, wall area 37.5 m^2) that was operated until December 2013 at Forschungszentrum Jülich, Germany [2].

The major plasma-facing components (PFCs) are the limiters of various kinds (marked in Fig. 1a), i.e. high heat flux (HHF) components that *limit* the plasma to protect other components from the direct impact of particle fluxes. As a result of plasma–wall interaction (PWI), plasma-facing components, especially HHF parts, undergo significant modification [3–7] under the impact of energetic particles. Material erosion occurs, followed by the transport of eroded species (ionized atoms and molecules) in the torus and, eventually, the deposition of those species that were not pumped out. Such deposition often occurs together with fuel atoms, i.e. hydrogen isotopes, forming mixed material layers referred to as co-deposits. The properties of co-deposits usually differ significantly from those of the original wall material. Considering these facts, topics of primary interest in PWI studies include the assessment of fuel retention in the wall and material lifetime. The latter calls for a detailed determination of the entire material migration cycle: erosion – transport – deposition – re-erosion, etc. [3,4,8,9]. These processes occur for every material exposed to plasma, but to various extents [4]. There is no ideal wall material that can meet a

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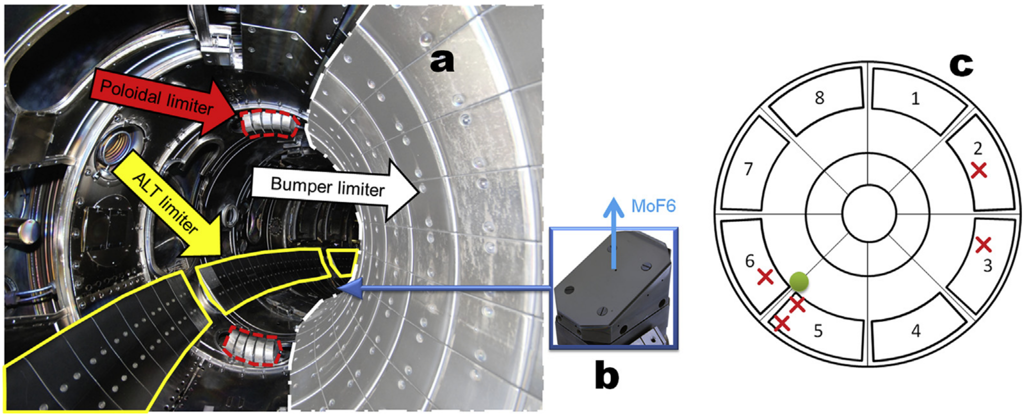

Fig. 1. (a) Toroidal view inside the TEXTOR vacuum vessel with all limiters (including the test limiter) marked, (b) a magnified image of the MoF_6 inlet and (c) a scheme of the ALT-II limiter seen from above, with the location of the MoF_6 gas inlet marked by a small circle and the analyzed tiles marked with crosses.

full range of requirements including high thermal conductivity, resistance to thermal shocks, low radiation losses by eroded impurity species, low erosion rate and low fuel retention. Carbon materials, especially graphite and carbon fibre composites, were considered as primary choices for a long time. As such, they were installed in most tokamaks, also in TEXTOR and, until 2009, in JET. However, high fuel retention connected to the formation of hydrocarbon layers motivated tests of other low-Z candidates, especially beryllium, for areas of moderate power loads (below 5 MW m^{-2}) and tungsten for HHF components. These two materials have been used since 2011 for the ITER-Like Wall in JET [10,11] and, after successful experiments [12,13], the same combination has been chosen for the wall of ITER. Preparations for ITER and subsequent reactor operation require comprehensive research regarding the behavior of high-Z metals in tokamaks, e.g. fuel retention and material migration under the impact of plasma impurities such as carbon, oxygen or other gases injected deliberately into the torus for plasma edge cooling [6,7,9,14]. The last category comprises predominantly nitrogen but also neon and heavier noble gases are tested. As a consequence, questions appear regarding nitrogen transport, reactivity with wall components and deposition that may lead to long-term retention. To answer these questions, tracer techniques are used [14,15]. They are based on the design of dedicated experiments in which one applies various marker tiles, wall probes and/or marker gases. A normal course of action is to develop such methods in a medium-size machine and then transfer the procedures to a large tokamak. The techniques have, thus, been developed and tested in TEXTOR, whose mission was strongly oriented towards PWI studies. Over the years, many experiments have been performed with rare, non-radioactive isotopes such as carbon-13 in the form of $^{13}CH_4$ to determine carbon transport [6–8,16–19], nitrogen-15 [20–24] and oxygen-18 [2,24,25]. For tungsten transport studies, a volatile hexafluoride, WF_6, has been used [9,26].

Following an experimental campaign, carried out with or without markers, some in-vessel components are retrieved from the torus and studied ex-situ. In the design of marker experiments there are at least two indispensable elements: availability of a marker and availability of methods to detect and measure it quantitatively on surfaces. Accelerator-based ion beam analysis (IBA) methods are very useful in studies of PFCs, as described earlier [27–29]. They are quantitative, highly sensitive, allow depth profiling even up to over 10 μm in some substrates and one can selectively determine light isotopes on surfaces. For instance, the analysis of deuterium by nuclear reactions is here of extreme importance. In the case of tracer experiments performed at the very end of experimental campaigns, one is interested in the composition of the surface region of PFCs or special probes. In this field, time-of-flight heavy ion elastic recoil detection analysis (ToF-HIERDA) plays a special role, as in a single measurement one may quantify light isotopes with atomic mass up to about 20 amu and also detect heavy species, although with poorer mass resolution (see Figs. 3 and 4 and the related paragraphs below for a more in-depth discussion on resolution). A detailed description of the technique is presented in Ref. [30].

The aim of this work was to determine, by ToF-HIERDA, the atomic composition of PFCs from TEXTOR in the 400 nm layer closest to the surface, and on this basis to conclude on high-Z material migration as well as to verify the particular usefulness of the technique in detecting light tracers. The distributions of a tracer, nitrogen-15, and a high-Z element, molybdenum, have therefore been in focus. Other species: boron, used for wall conditioning [31,32], ^{14}N from edge cooling discharges and fluorine from the molybdenum hexafluoride that was used to provide molybdenum in a gas state, have also been studied.

2. Experiment

The experiments were performed in the TEXTOR tokamak (see Fig. 1a). Its main PFCs are: the belt toroidal limiter, also known as the Advanced Limiter Test (ALT-II), poloidal limiters at the top and the bottom of the machine and the inner bumper limiter being a shield for the Dynamic Ergodic Divertor (DED). Molybdenum hexafluoride and nitrogen-15 were puffed into discharges heated by neutral beam injection. The procedure was similar to that employed in the case of WF_6 puffing in earlier experiments [9]. Tungsten has been used in TEXTOR in many other experiments and, as a consequence, a relatively high W background was expected to be seen on many PFCs. This fact motivated the choice of molybdenum to examine high-Z transport as a substitute for tungsten.

MoF_6 and $^{15}N_2$ were introduced during 31 and 22 discharges respectively. The typical discharge time was 8 s. $^{15}N_2$ puffing took place between 1 and 5 s, whereas MoF_6 injection was done between 0.8 and 1.8 s (in all but two discharges, during which it lasted until 2.8 s instead). A total of $1.4 \cdot 10^{21}$ MoF_6 molecules and $5.3 \cdot 10^{21}$ ^{15}N atoms were estimated to have been introduced into the machine. Approximately 30%–50% of the MoF_6 entered the plasma and the rest is assumed to have been retained in the inlet system.

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