TRACER TECHNIQUES IN STUDIES OF MATERIAL TRANSPORT IN THE PLASMA EDGE OF TOKAMAKS

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C-13 marked methane and tungsten-rhenium coated plates were used at the TEXTOR tokamak as tracers for studies of the material transport, its erosion and re-deposition. The results are discussed in terms of processes (physical sputtering, chemical erosion, prompt re-deposition) underlying the material transport and the change of morphology of targets exposed to the plasma. The issue of fuel inventory is also addressed.

1. Introduction

The term "tracer" denotes an alien agent introduced deliberately to a studied system in minute quantities. The introduced agents must also be reasonable harmless to the system under examination. Tracers are applied in many fields of science and technology in order to accomplish a conclusive determination of a reaction mechanism, distribution of components, flow direction, velocity, etc. An important point in using tracers in controlled fusion devices is the determination of a long-range (i.e. meters) and a short-range (local, i.e. cm) material transport in the plasma. Such studies improve the understanding and a detailed recognition of processes resulting in material erosion and re-deposition. These processes lead to a drastic modification of plasma facing components (PFCs) due to material mixing [1]. Therefore, they are decisive for the material lifetime and fuel inventory.

The intention of this contribution is to present both the experimental procedure and a concise overview of recent results obtained in experiments aiming at the determination of carbon transport (C-13 tracer) and the erosion rate of high-Z metals (e.g. W tracer). In brief, the reasons to study those elements are related to the following facts.

- Graphite-based PFCs are used in most of nowadays devices [2-5] and carbon (^{12}C) is the major plasma impurity species,
- Carbon eroded from PFCs is re-deposited (co-deposited) - after being transported to another location – together with vast amounts of fuel atoms [6-9] and this results in a significant tritium inventory in case of the operation with D-T plasmas [10,11]. The determination of the amount of carbon transported and the location of deposition zones is then crucial for next-step machines.
- Tungsten is considered as a first wall material for the next-step machines [12-14].

The experiments were carried out in the TEXTOR tokamak (Institute of Plasma Physics of the Forschungszentrum Jülich, Germany) whose scientific programme is strongly focused on plasma – surface interactions. It also emphasizes the testing of candidate materials and studies of impurity production and transport in the plasma edge. Fig. 1 shows the inner structure of the torus: an inconel liner, various types of graphite limiters and rf antennas protected by graphite screens. Fig. 2 exemplifies a limiter tile covered with a thick co-deposit containing a mixture of plasma impurity (mainly carbon) and fuel species. Studies of such PFCs give the information on the net erosion and re-deposition effects and on the long term fuel accumulation in a tokamak. In order to recognize detailed mechanisms deciding the material migration tracer techniques are to be applied.

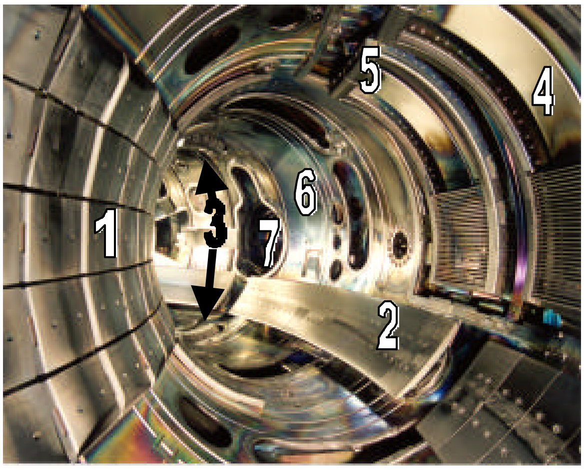

Fig. 1. View along the toroidal direction inside the vacuum vessel of the TEXTOR tokamak: bumper limiter (1); toroidal belt limiter (2); bottom and upper poloidal limiters (3); ICRF antennas (4); antenna protection screens (5); inconel liner (6) with ports (7) for pumping ducts, plasma diagnostics and plasma heating with NBI.

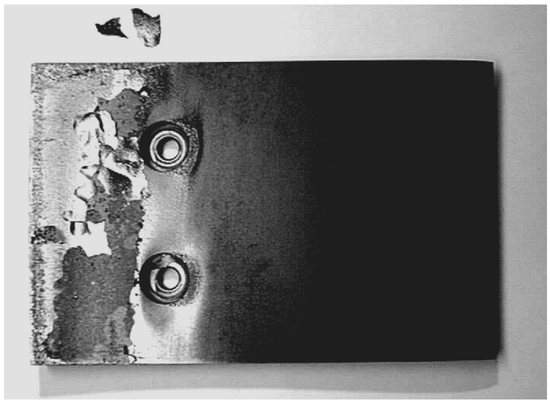

Fig. 2. Graphite tile of the toroidal belt limiter after 14 200 s exposure to the plasma. The erosion zone at the outer edge of the limiter blade (the right side) and the re-deposition zone with thick flaking layer (in the central part of the limiter blade, the left side) can clearly be distinguished.

2. Experimental procedure

An experimental approach to the study of transport phenomena involves the application of plasma diagnostics, surface probes and tracer materials. The tracers are introduced into the plasma edge either by injection of reactive gases (e.g. $^{13}CH_4$, SiD_4, ^{18}O, $B(CH_3)_3$), by ablating high-Z tracer material using laser beams or by exposing surface probes coated with well defined sandwich-type layers of high-Z (W, Re) and low-Z (C, B) elements. The amount and distribution of eroded, transported and then re-deposited species is determined by means of several surface-sensitive methods. Surface study was carried out using secondary ion mass spectrometry (SIMS) for depth profiling, electron probe microanalysis (EPMA), thickness determination from interference colours (colorimetry), scanning electron microscopy (SEM) and ion beam analysis (IBA) methods such as nuclear reaction analysis (NRA), Rutherford backscattering spectroscopy (RBS) and enhanced proton scattering (EPS).

In studies of carbon transport a predetermined amount of $^{13}CH_4$ molecules was puffed into the plasma through an inlet hole in an aluminum plate located 1 cm deep in the scrape-off layer (SOL). The aim was to determine the carbon deposition efficiency (i.e. the ratio of species deposited locally in the vicinity of the inlet hole to the amount transported in the torus: $^{13}C_{local}$ / $^{13}C_{long\ range}$) and to understand the process in terms of modelling with the ERO-TEXTOR code [15,16]. In the second experiment a graphite plate was coated with approx. 120 nm W + 120 nm Re layers (rhenium as a diffusion barrier for W into carbon) and then siliconized and partly carbonized. During the exposure to the plasma a part of the plate was shielded with a mask in order to clearly separate the exposed and non-exposed areas (see Fig.

4 a). In addition, the plate edge created a shadowed region. The aim was to assess the erosion rate of the high-Z layer and the transport to a shadowed area.

3. Summary of results

Fig. 3 shows the plate exposed during the $^{13}CH_4$ injection and the distribution of ^{13}C (injected) and ^{12}C (deposited from the plasma) in terms of the isotopic ratio. The distribution is highly non-uniform and the ratio reaches its maximum value 2-3 cm from the inlet hole and then it decreases in the toroidal direction. The results of surface studies show that less than 1 % of the injected ^{13}C is deposited locally ($^{13}C_{local}$ / $^{13}C_{long\ range}$ < 0.01). The rest becomes disintegrated and transported as ions to other locations in the torus, i.e. to the deposition zones on the blades of the toroidal belt limiter [9]. To assess the long-range transport caused primarily by chemical erosion of carbon a collector-type probe exposed in the SOL plasma. The fraction ^{13}C / ^{12}C + ^{13}C of about. 0.27 was measured.

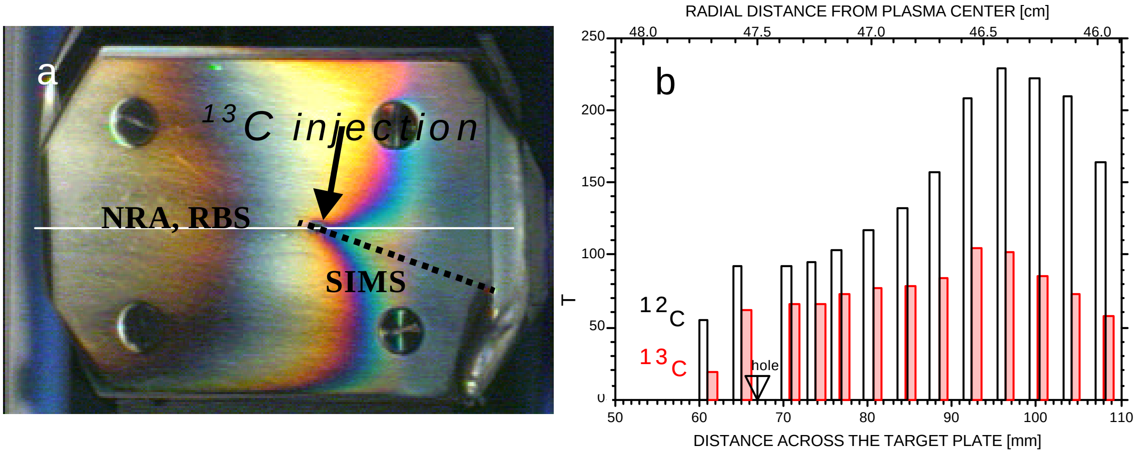

Fig. 3. Injection of $^{13}CH_4$ into the SOL. (a) Deposition pattern of ^{12}C and ^{13}C on the Al plate; lines of analyses are marked. (b) Distribution and concentration of C isotopes on the plate measured with SIMS.

Fig. 4 shows the W + Re coated plate before its exposure to the plasma. The line scan for the high-Z metals distribution along the plate after the exposure to the plasma is plotted on the accompanying graph. One perceives that the metal film disappeared totally, as a result of

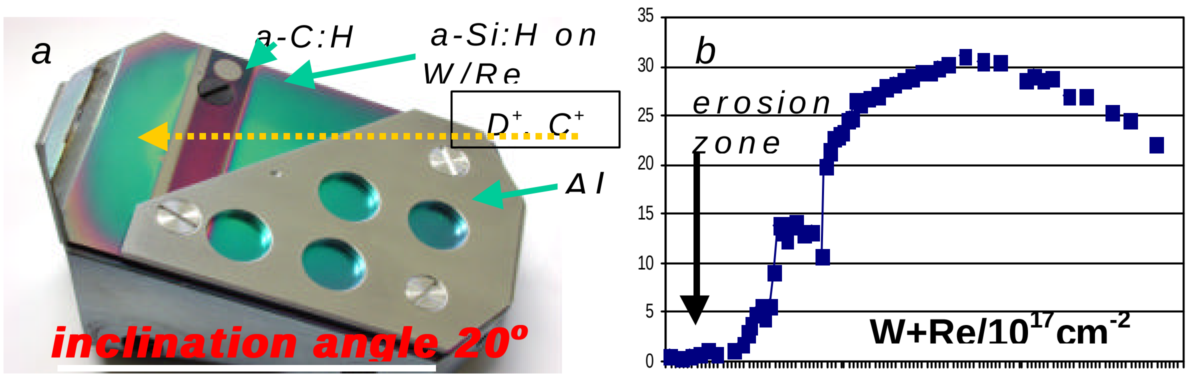

Fig. 4. Erosion of W+Re coated plate. (a) Experimental set-up. (b) Distribution and concentration of high-Z metals measured with RBS following the layer exposure to the plasma.

physical sputtering, in the net erosion area. Taking into account the initial film thickness (240 nm) and the plate exposure time (150 s), the lower level of the erosion rate of high-Z metals is estimated to be 1.6 nm s^{-1}. The threshold energy for sputtering of W and Re by D^+ ions is around 230 eV (calculated according to [17]), whereas the edge electron temperature at TEXTOR for the reported experimental conditions is about 60 eV [18]. giving the accelerating sheath potential ($5kT_e$) [19] of approximately 300 eV, i.e just above the threshold value. From this fact, one concludes that the erosion of high-Z metals is mainly stimulated by plasma impurity species, e.g. carbon (E_{th} = 49 eV), boron (E_{th} = 54 eV) or silicon (E_{th} = 36 eV), because, under the experimental conditions, the erosion rate by D^+ ions does not exceed 0.3 nm s^{-1}.

4. Concluding remarks

We have applied various tracer elements for detailed studies of material erosion and migration under the plasma operation. Fast and long range migration of carbon has been proven in experiments involving C-13 marked methane. In experiments with high-Z metal tracers, the erosion rate of those elements has been measured and the major species involved in the erosion process could be inferred. These measurements help to assess the material lifetime in next step machines operated with the wall consisting partly of high-Z first wall components. Silicon and boron containing compounds were used as markers in several other experimental campaigns.

The interest in application of tracer methods is growing. Therefore, it requires the design and construction of new tools. Recent progress in the development of edge diagnostic methods at TEXTOR have resulted in the construction of a fast reciprocating probe penetrating into the plasma. This opens a new field in studies of plasma - material interactions. First experiments with tungsten coated targets have already been carried out. Tracer techniques, based on a controlled puffing of silane and C-13 methane as transport markers, have also been implemented into the JET-EFDA workprogramme.

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