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Particle collection at the plasma edge by a fast reciprocating probe at the TEXTOR tokamak

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Abstract

A fast reciprocating probe system capable of transferring different types of heads has been constructed and implemented at the TEXTOR tokamak for diagnosing the plasma edge. It gives the possibility of using a particle collector technique to extend studies of material transport from the scrape-off layer to the near plasma edge. For the first time, the system was used for exposures of graphite samples (pure and coated with a-C:H or W) at positions both within and outside the last closed flux surface. Various surface analysis methods were applied to investigate the probe morphology and, by this, to determine radial deposition profiles of boron impurities and deuterium. The profiles for boron are remarkably flat whilst those for deuterium are characterised by a steep decay with the e-folding length of approximately 15 mm. On tungsten-coated samples almost no deuterium was found, most likely because of little carbon co-deposition, shallow implantation and low trapping coefficient of deuterons in the tungsten layer. Reconstruction of experimental results by means of a multifluid TECXY code helped to identify the contribution of impurity sources (limiters, wall) to the observed radial distribution of species.

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1. Introduction

Detailed characterization of the plasma edge and the scrape-off layer (SOL) requires many methods enabling the determination of material transport, i.e. the temperature, density and composition of particle fluxes. This may be accomplished combining electrical and surface collector measurements of particles. Fast reciprocating probes have been used in several machines [1–6] mainly for the determination of ion and electron temperatures. On some occasions, at JET [7], the heads of a retarding field analyser and a fluctuation probe were analysed ex situ with surface sensitive methods in order to recognise the species deposited and to conclude a preferential flow direction of the deuterium background plasma and impurities. These analysed probes, however, were facing many discharges under various plasma operation scenarios and they were exposed at many different radial positions. Therefore, only deposition integrated over many shots could be assessed. This is because the use of beryllium and tritium at JET has limited the access to in-vessel components and, as a consequence, the possibility of a frequent probe exchange.

Recently, a new fast reciprocating probe system has been designed and constructed at the TEXTOR tokamak. This was done in connection with the implementation of a dynamic ergodic divertor (DED) [8] and the necessity of preparing diagnostic tools capable of

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characterising the plasma edge under new experimental conditions. Secondly, the DED installation has reduced the number of available diagnostic ports. As a consequence, several diagnostic systems must be combined. In the case of edge and SOL probes the solution was the development of a transfer system designed as a multi-user facility equipped with an interlock and a unified coupling module to assure fast exchange of probe heads: Mach, multi-pin Langmuir and a surface collector. The transfer system for slow and fast movements was ready before the machine shutdown for the DED installation. For the first time it was used for exposure of a surface collector operated in a fast reciprocating mode. Measurements with a collector probe are based on the exposure of a solid surface to the plasma, followed by analysis of the targets with surface sensitive methods. One measures net deposition (co-implantation) rates of ions. Discrimination between fluxes of different species is the technique's major advantage. The main purpose was to determine the deuterium and impurity deposition rates on graphite targets inserted 1–2 cm inside the last closed flux surface (LCFS) and, from this, to infer whether there is a preferential flow direction. Another motivation was to extend earlier measurements, done with a stationary probe [9–11] operated in the SOL, into the very plasma edge. This experiment was carried out at TEXTOR for the first time with several additional aims such as a performance test of the transfer system and the probe head itself. Last but not least, we wanted to gather results under the limiter configuration of TEXTOR. In the near future they will be compared with data obtained in the presence of the DED shaped edge.

2. Experimental and modelling procedure

2.1. Probe experiments

The probe is moved to the vacuum vessel through a horizontal port at the equatorial plane. It is located 45° poloidally from the TEXTOR main limiter: a toroidal belt limiter (ALT II) defining the minor radius at 46 cm. An inclination angle (10°) of the probe system axis with respect to the radial direction results in non-equal probe immersion into the plasma: 10 mm deeper on the electron drift side than on the ion side. Three drives provide the rotation (rotation speed up to 3 Hz, precision in positioning 0.3°) as well as two modes of linear transfer: (i) slow motion (up to 20 cm/s) for probe positioning in the SOL and (ii) fast reciprocation (5 m/s) into the plasma. For exposure of surface collectors the probe is first moved slowly to the SOL and then reciprocated (0.4–1.0 m/s) during a selected part of a discharge. In the experiments described below, the entire reciprocation stroke lasted 200 ms during which the probe end travelled 2 cm deep inside the LCFS and was positioned there for 100 ms. The temperature rise of the housing during a stroke did not exceed 600 °C in ohmic discharges.

Fig. 1. Surface collector probe: (a) a tantalum housing with 2 mm wide slits, (b) a graphite holder with ten groves for flux collecting substrates and (c) flux collecting substrates.

Fig. 1 shows the probe head. It consists of an 80 mm long tantalum housing with 2 mm wide slits open to the ion and the electron drift directions and a graphite ($\phi = 50$ mm) sample holder with 8 mm wide slots for ten sets of samples, i.e. five exposures can be made before exchanging the collectors. When selecting the substrate and housing materials we had to take into account safety of the probe operation and still not compromising the experimental goals. Tantalum was chosen for the housing. Other materials resistant to thermal shock, such as graphite (used for SOL probes) and boron nitride, were eliminated in order to avoid local contamination with boron [7] or carbon as these are the major impurity species to be studied in the edge plasma of TEXTOR. Carbon originates from graphite plasma facing components whereas boron is present due to the boronizations. Aluminium or silicon, though the most appropriate substrates for impurity collection, could not be used due to the risk of melting or cracking. Instead, collectors based on EK98 graphite were used: bare polished substrates, coated with an amorphous carbonised film (a-C:H) or with a 200 nm thick tungsten overlayer. The use of graphite targets certainly limited the chance of direct carbon tracing, but the behaviour of impurities represented by boron could be studied (the time interval between the last boronization and the exposure was around 1000 plasma operation seconds). This approach is justified because both elements (C and B) are eroded from the same locations as machine's impurities. Secondly, the use of low-Z (graphite) and high-Z (tungsten coated) collectors allowed some conclusions regarding the deuterium deposition mechanism.

Twenty targets (ten bare graphite, eight a-C:H coated graphite with a W interlayer and two tungsten coated) were exposed during either ohmically heated pulses or during the second ohmic phase of discharges additionally heated by neutral beam injection (NBI). Exposures within the NBI phase were not performed in order to avoid possible overheating and damage of the probe. The amount and distribution of deuterium and boron on the exposed surfaces were determined using nuclear reaction analysis (NRA) assuring the detection limit of those species better than 1×10^{15} cm^{-2}. Measurement by means of Rutherford backscattering spectroscopy (RBS), electron probe microanalysis (EPMA) and secondary ion mass spectrometry (SIMS) generated additional information on surface morphology.

2.2. Modelling

For the reconstruction of experimentally measured radial profiles of impurity species in the plasma edge the two-dimensional TECXY transport code was used [12–14]. Like most other 2D computational plasma edge fluid models, the code is primarily based on classical transport equations derived by Braginskij [15]. The model describes electrons and various ion species in their different charge states as separate fluids. The transport along field lines is assumed to be classical whereas the radial transport is considered anomalous with prescribed radial transport coefficients of the order of Bohm diffusion following an Alcator-like scaling (i.e. inversely proportional to density) in the transition layer. All ion species have the same temperature T_i, which can be different from the electron temperature T_e. Equations of different fluids are coupled by electrostatic, friction and thermal forces as well as by atomic processes such as collisional ionization, recombination excitation and charge exchange. In order to consider drift motions and currents in the tokamak boundary layer, additional equations were added to the TECXY-code, which have been obtained from the radial and diamagnetic components of Ohm's law and the equation of motion.

The dynamics of deuterium and impurity neutrals in the neighbourhood of the ALT-II limiter is described by the analytical model, which accounts in a self-consistent way for recycling of plasma ions as well as for sputtering processes at the limiter plates. Only physical sputtering by deuterium ions and self-sputtering of carbon atoms are considered in the model. Carbon atoms released from the wall are also described by an analytical model. We assumed that they are produced only due to physical sputtering with a constant (for simplicity) sputtering yield. The aim of calculations was to identify ionic species in the edge and to assess the contribution of impurities generated at two sources (limiters and wall) to the material erosion and transport.

3. Results and discussion

3.1. Probe measurements

Plots in Fig. 2 exemplify the deuterium content detected along the radial direction on two sets probes. Set (1), bare EK98 graphite, was exposed during the ohmic pulse, whereas set (2), graphite coated with amorphous C:H film, during the second ohmic phase of a pulse additionally heated with NBI. Each pair of lines represents concentration of species deposited from the electron (radial distance from 45.2 to 47.2 cm) and the ion drift direction (radial distance from 46.4 to 48.2 cm). This shift in the starting point for ion collection is related to the difference in the depth of probe insertion to the plasma on both sides (see Experimental 2.1). Deuterium contents at the 'peak' position, i.e. for the end of the probe in the radial direction towards the plasma ($r = 45.2$ cm), are found in the range $3–7 \times 10^{16}$ D-atoms cm^{-2} dependent on the exposure conditions. These amounts reflect effective deposition rates of deuterium (the quantity measured with a collector probe technique) of the order of 10^{17} D-atoms cm^{-2} s^{-1}. They

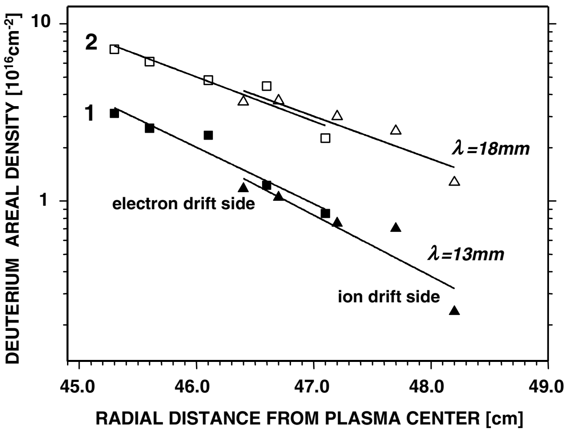

Fig. 2. Radial profiles of deuterium deposited on graphite (1) and a-C:H coated probes, (2) deposition measured on the electron (squares) and the ion (triangles) drift side is shown.

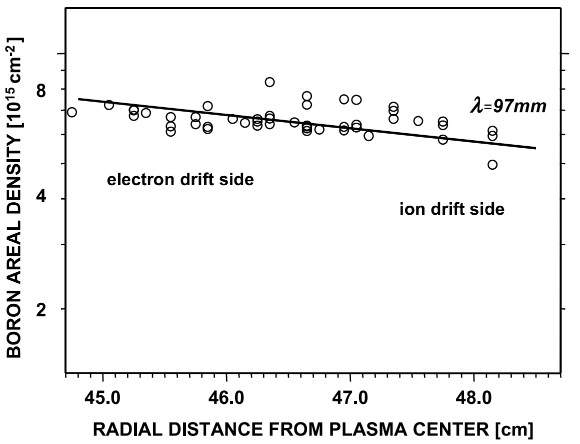

Fig. 3. Radial profiles of boron deposited on several graphite and a-C:H coated probes.

account for approximately 1% of the D^+ flux in the plasma edge measured with spectroscopy [16]. This is related both to the reflection of D ions and to the release of co-deposited species by erosion. The difference in the deposition efficiency observed both for D and B during purely ohmic discharges and NBI heated pulses suggests that after the NBI phase edge ion temperatures were higher leading to a deeper implantation of species. Secondly, the implantation depth into a-C:H layer maybe somewhat larger than into bare graphite targets.

On W-coated graphite samples very small amounts of deuterium (10^{14} cm^{-2} level) were found whereas neither carbon (detection limit around 5×10^{16} cm^{-2}) nor boron could be detected. This indicates high re-erosion rate of carbon deposited on tungsten (at this radial position) and, that the deuterium retained on these samples is most probably implanted directly in a shallow layer of the tungsten coating. The result shows both minute implantation of species and confirms also small trapping efficiency and retention of deuterium in tungsten [17,18].

From the plots in Fig. 2 one infers very similar decay characteristics of the D flux on both sides of the probe: an e-folding length, λ, of around 15 mm. This agrees well with flux gradient measurements in the near edge using helium beam diagnostics [19] and in the deeper SOL (20–70 mm) using the previous arrangement of the collector probe at TEXTOR [9,20]. The profiles give no evidence of a preferential flow direction of the deuterium background plasma in the near limiter layer, i.e. in the vicinity of the LCFS.

Radial profiles of boron, shown in Fig. 3, are decidedly different, because they are rather flat with a corresponding e-folding length between 6 and 10 cm. They also distinctly differ from previous ones recorded for impurity species with collector probes located deep in the SOL, i.e. the first point measured minimum 14 mm outside the LCFS. In that region, profiles of D and other species were similar and characterised by e-folding lengths not exceeding 20 mm. In this sense, the investigation performed with the fast reciprocating system has yielded qualitatively new results. They clearly reflect the fact that the place of origin of the deposited deuterium and impurities is different. In the case of impurities, one has to identify the relative contributions of erosion efficiency of the wall and limiters to the overall impurity release and transport.

3.2. Modelling

Calculations were made for carbon assuming only physical erosion by D fluxes to the wall and D and C induced erosion at the limiters. Chemical effects, i.e. the major pathway of carbon erosion [21], were not included. Under such conditions one expects the results for C and B impurities to be fairly similar. Given the electron edge temperatures at TEXTOR ($T_e \approx 60$ eV for ohmic and ~100 eV for NBI heated pulses) and the ionization potentials of B and C, the species would be left with two inner shell electrons, B^{3+} and C^{4+}, respectively.

The simulations were performed for a number of cases assuming different contributions of the ALT II at $r = a = 46$ cm and the wall ($r = 55$ cm) as impurity sources. As expected, if the wall was treated as the only source, the measured flat profiles could not be reconstructed. Plots in Fig. 4 show a complete set of results for two more realistic cases (a) the impurity release occurs solely on the limiter and (b) the eroded species originate from the limiter (due to sputtering and self-sputtering) and from the wall assuming only constant sputtering yield by D ions.

Two clear messages can be inferred. Carbon C^{4+} is the major species being present in the near edge layer

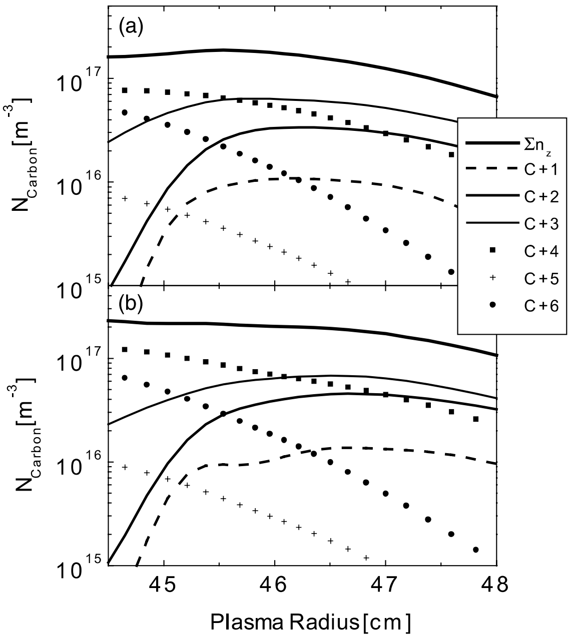

Fig. 4. Computer reconstruction of edge profiles for carbon ions: (a) profiles assuming the impurity production on the limiter only and (b) profiles assuming the impurity production partly on the limiter (physical sputtering and carbon self-sputtering) and on the wall.

from 45 to 48 cm. Fairly flat radial decays, $\lambda \approx 4$–6 cm, are reconstructed taking into account both the limiters and the wall as impurity sources. The profiles for impurity release from the limiter only are less uniform and more steep towards the SOL. Similar results have been obtained for low and high density conditions. These results are considered representative also for boron with B^{3+} as the main ionic species in the plasma edge.

4. Conclusions

First measurements with a surface collector operated in a fast reciprocating mode in the near plasma edge at TEXTOR were performed. These experiments allow some conclusions regarding both technical aspects of the probe design and ion flux measurements. The choice of tantalum as a material for the probe housing was proven right as no local erosion was observed: i.e. no contamination of the plasma occurred and no local deposition of Ta on the exposed graphite substrates was detected (the detection limit of Ta with RBS is lower than 1×10^{13} cm^{-2}). Such reliable protection of the samples allows us to plan next experiments with other – than graphite – flux collecting substrates (e.g. Ti, Si) in order to study the deposition of carbon impurities. This will be important because with the present probe arrangement only deuterium and boron net deposition rates on surfaces exposed to plasma flows inside the LCFS could be assessed. Radial decays for the fuel and impurity species in the near limiter region significantly differed one from another. A steep decay of the D flux ($\lambda = 15$ mm, the same as measured with other methods [19]) and a flat profile of boron, with a decay length of over 6 cm, were observed. Computer modelling with the TECXY code reconstructed the impurity profiles indicating that contribution of two impurity sources (from the wall and from the limiter) to the distribution of species in the plasma edge is essential. The ratio of impurities released from the limiter and from the wall has been assumed to be 9:1. One has to take into account, however, that the surface area of the wall is approximately ten times larger than the area of the limiters. These measurements carried out under the limiter configuration of TEXTOR will be useful for comparisons when the plasma edge is controlled by dynamic ergodization.

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