Journal of Nuclear Materials 390–391 (2009) 179–182

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

In-situ measurements of carbon and deuterium deposition using the fast reciprocating probe in TEXTOR

B. Emmoth [a,*], A. Kreter [b], A. Hallén [a], M. Jakubowski [b], M. Lehnen [b], A. Litnovsky [b], P. Petersson [d], V. Philipps [b], G. Possnert [d], M. Rubel [c], B. Schweer [b], P. Sundelin [c], B. Unterberg [b], P. Wienhold [b], TEXTOR team

[a] KTH, School of Communication and Information Technology, Microelectronics and Applied Physics, Materials Physics, Association EURATOM – VR, Electrum 229, 16440 Kista, Sweden
[b] Institut für Energieforschung – Plasmaphysik, Forschungszentrum Jülich, Association EURATOM – FZJ, Trilateral Euregio Cluster, Germany
[c] Alfvén Laboratory, Royal Institute of Technology (KTH), Association EURATOM – VR, 10044 Stockholm, Sweden
[d] Tandem Laboratory, Uppsala University, EURATOM – VR, Box 529, 751 20 Uppsala, Sweden

ARTICLE INFO

PACS:
52.40.Hf

ABSTRACT

Silicon samples were exposed in the scrape-off layer of the TEXTOR plasma using a fast reciprocating probe, with the aim of studying carbon deposition and deuterium retention during Dynamic Ergodic Divertor (DED) operation. Separate samples were exposed for 300 ms at the flat-top phase of neutral beam heated discharges. The exposure conditions were varied on a shot-to-shot basis by external magnetic perturbations generated by the DED in the $m/n = 3/1$, DC regime, base configuration. Nuclear Reaction Analysis (NRA) was used to characterise collector sample surfaces after their exposure. Enhanced concentrations of both carbon and deuterium (C 3–10 $\times$ 10^{16} at./cm^2, D 8–60 $\times$ 10^{15} at./cm^2) were found. The D/C ratio was less than unity which indicates that most of the carbon and deuterium were co-deposited. Carbon e-folding lengths of about 2 cm were found on both toroidal sides of the probe independent of DED perturbations.

1. Introduction

One established method to characterize impurities and deuterium in the scrap-off layer of fusion plasma is based on the use of collector probes [1–3]. At TEXTOR the fast reciprocating probe (FRP) has previously been explored for studies of deuterium and boron fluxes in the plasma [4]. However it is not possible to study carbon with this design since the collectors samples were made of carbon as well.

Measurements reported here are aimed at studies of carbon made possible due the use of single silicon crystals as the collector material in the FRP. The main advantage with the FRP is temporal resolution by fast sampling of the plasma. Low impurity abundances in silicon make sensitive carbon and deuterium measurements feasible. Standard ion beam analysis techniques, Rutherford Backscattering Spectrometry (RBS) and NRA, allow convenient simultaneous analysis of deuterium and carbon. It is, however, important to compare the results with complimentary measurements as well as theoretical modeling to reveal relevant information, such as true fluxes.

The second goal of this work was to characterize the TEXTOR tokamak after modification of the first wall. The Dynamic Ergodic Divertor (DED) [5,6] was installed in 2001–2002 to reduce the heat load of the strike points and to improve control of particle transport [7]. Specifically three different conditions were studied, all with neutral beam heating: Without DED perturbation, with low DED perturbation and with high DED perturbation.

2. Experimental

The FRP is located at the mid-plane of the tokamak between the poloidal coils #5 and #6 and can be equipped with exchangeable measuring devices. For measurements presented here a surface deposition unit, shown in Fig. 1, was used. It consists of an inner carbon sample holder with slots for ten rows of collector samples and an outer molybdenum shield with two slits, 4 mm wide and 60 mm long, at opposite sides of the shield. By using silicon as the collector material, it is possible to analyze both deuterium and different impurities originating from the plasma, such as carbon.

The FRP was initially located at parking position with the probe tip at minor radius $r = 49$ cm. The ten collector samples inside the FRP were placed in a position not exposed by the slit openings. During a shot, the FRP was moved in at 800 mm/s to the exposure

* Corresponding author.
E-mail address: emmoth@kth.se (B. Emmoth).

0022-3115/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2009.01.162

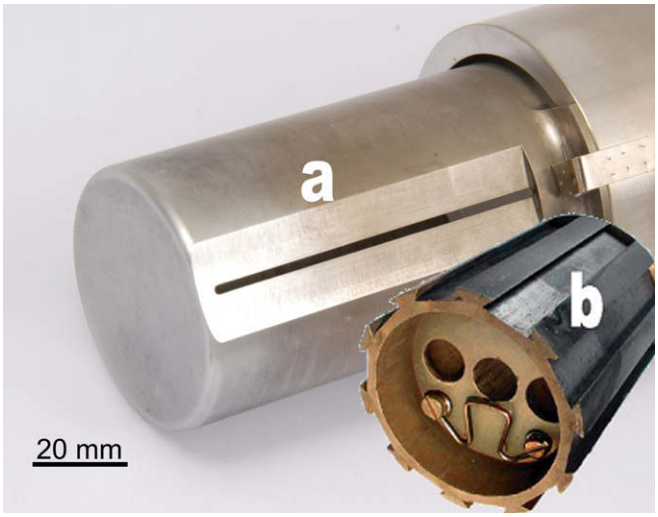

Fig. 1. The molybdenum housing marked a, showing one of the two 4 mm wide and 60 mm long slits that are in the ion and electron facing directions. The rotatable sample holder normally located inside the housing is marked b.

position at $r = 46$ cm with the last-closed flux surface at $r = 45.7$ cm defined by the DED target. At the exposure position the inner sample holder was rotated 18° in 50 ms thereby exposing the collector samples to plasma fluxes through the two slits, one facing the electron drift side, the other the ion drift side. The collector samples were exposed for 300 ms each during constant plasma conditions. Then the holder was rotated back to a non-exposed position and the FRP linearly retracted to the original parking position.

The samples were exposed at three different plasma conditions: Non-DED discharges, DED with low perturbation and DED with high perturbation, covered by shots #105020, #105025, #105026. The probe exposure caused moderate increase of the impurity level in the plasma, reflected in an increase of the line-integrated plasma density of up to 5%. For the high perturbation shot, #105025, the so called pump-out effect [7] was observed as well as less disturbance from the probe compared to what was observed for the low perturbation shot.

The silicon collector samples were analyzed at the Tandem Accelerator at Uppsala University by simultaneous NRA and RBS using a ^{3}He beam. Carbon and deuterium concentrations were determined by protons from the following nuclear reactions: $^2H(^3He,p)^4He$ [8] and $^{12}C(^3He,p_{0,1,2})^{14}N$ [9]. These reactions give distinct spectra with almost background free peaks along with ^{3}He ions that have backscattered from the sample (Fig. 2). To efficiently capture the high energy protons (up to 12 MeV) a thick solid state detector (1500 μm depleted depth) was used. To improve the energy resolution in the region representing ^{3}He ions backscattered from metals in the sample and to reduce statistical error, a second solid state detector was installed. The signal from deuterium was measured from the thick NRA detector while carbon was detected from the p_0 and p_1 peaks in both the NRA and the thinner RBS detector. The sensitivity in metal detection are to some degree limited by pile up from the more intensive silicon backing and by interference from other metals and the p_2 peak from the carbon reaction.

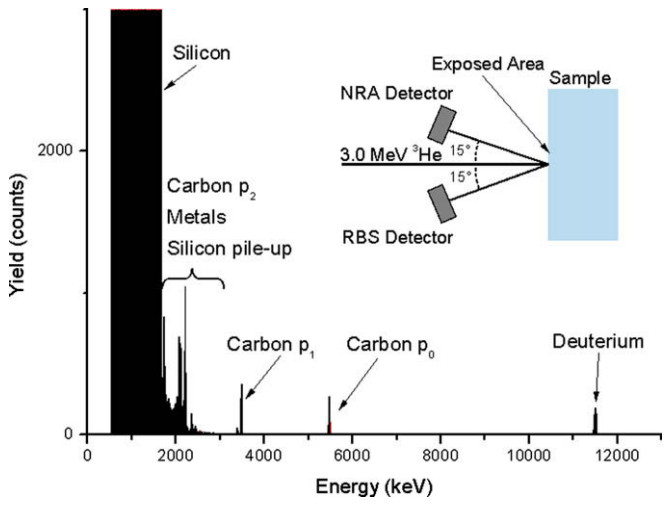

Fig. 2. A typical NRA spectrum acquired by the thick solid state detector showing signals from both carbon and deuterium nuclear reactions as well as backscattered ions.

3. Results and discussion

To investigate the background values for collection samples and background due to contamination, samples installed in the FRP but not exposed to the plasma were analyzed. Concentrations of deuterium between 1.0×10^{15} and 1.5×10^{15} at./cm^2 and of carbon between 1×10^{16} and 2×10^{16} at./cm^2 was found and corrected for during the analysis of exposed samples. The unexposed collector samples exhibit high deuterium levels compared to the natural abundance. Furthermore significant amounts of Mo were found which together with the enhanced deuterium concentration indicate a small redistribution of plasma related materials inside the FRP housing. It is probable that parts of the carbon background have the same origin since the holder is made of carbon.

The carbon concentration results are presented as net deposition rates for the 300 ms exposures (Fig. 3). An exponential decay is fitted to the data and presented along with the results. The resulting decay constant, the e-folding length λ in cm, is presented in the legend. The statistical error in the measured carbon concentration is approximately 5%. For lower concentration, at distant r positions, the background subtraction dominates the uncertainty. Since e-folding length is a relative value, it will not be affected by e.g. uncertainty in cross sections. The total error is 10–15%).

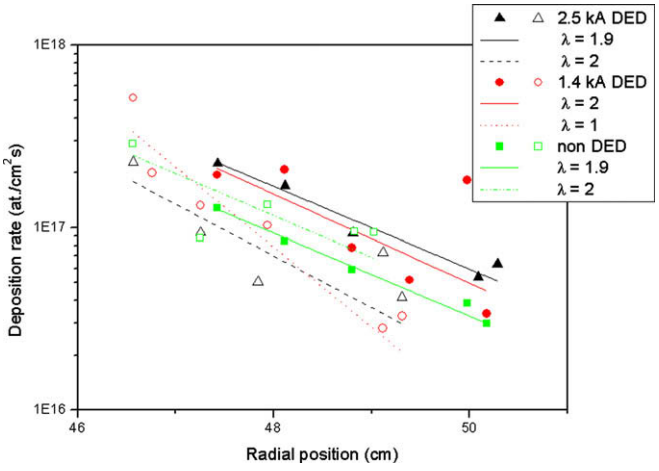

Fig. 3. Carbon deposition rates for three plasma conditions: Non-DED (green squares), low perturbation DED (red circles) and high perturbation DED (black triangles). Filled symbols correspond to ion facing side of the sample, and open to the electron facing side. Fitted lines correspond in all cases to the measurements, full lines for ion side and dashed lines for electron side. The e-folding length (in cm) in each case is shown in the insert. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For the non-DED case as well as for the DED perturbed cases the e-folding length is approximately 2 cm, for both ion and electron facing sides. Measurements of carbon for unperturbed conditions reveal higher deposition rate on the electron side of the probe compared to the ion side by about 25% at the same radial position. This is similar to what previously has been found for impurities [1] and is explained by longer field line connection length to the wall on the electron side. However, for measurements under perturbed conditions the trend is the opposite with higher values at the ion side than at the electron side. In the pump-out case the difference reaches a factor of two.

Modeling of the magnetic field structure [5] shows that, for all exposures, the probe is in the laminar region, i.e. the connection length is relatively short and does not show stochastic behavior. Previous measurements [10] show that in the laminar region both the plasma density and the plasma temperature are reduced by the DED perturbation. For the high energy field side other measurements have shown no average reduction in CIII and possible small decrease in CV spectroscopic signals [11] during pump-out. This is interpreted as an increase in carbon flux caused by DED operation. For measurements presented here the average net carbon deposition is actually slightly higher (~10%) for the high perturbation case in comparison to the non perturbed case. However, most striking is the increase and decrease at the different sides of the probe.

In Fig. 4 the deuterium deposition rates on the silicon collectors are shown. Only in case of the ion facing side it was meaningful to determine an e-folding length λ. The statistical error is about 10% and the error due to variations in background is smaller than for carbon. It should be noted, however, that net measurements of deuterium deposition rates are shown in the figure. The influx is very high but the deposition competes strongly with sputtering and erosion that will affect the values. The detected net deposition rates for deuterium are in the order of 1% of the true flux and several different parameters influences the net deposition. Similar effects are also possible for carbon but to a much lower extent [12].

For all three exposures condition the deuterium deposits show a clear difference between the ion side and the electron side. The ion side of the non-DED discharge has an e-folding length of approximately 1.2 cm. This compares well with the value measured with the probe before the DED installation of around 1.5 cm [4] but in that case on both sides of the probe. In the cases of low and high perturbation by the DED 1.9 cm and 2 cm were found respectively. These values compares well with what is observed for carbon. The

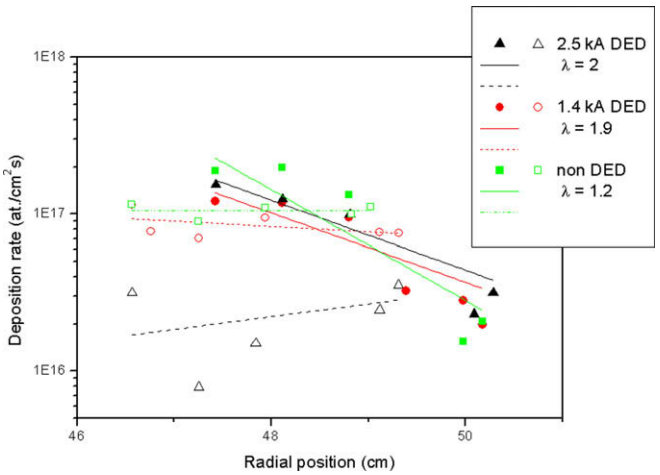

Fig. 4. Deuterium deposition rates for three plasma conditions. The symbols correspond to those in Fig. 3. e-folding lengths were only determined for ion facing directions.

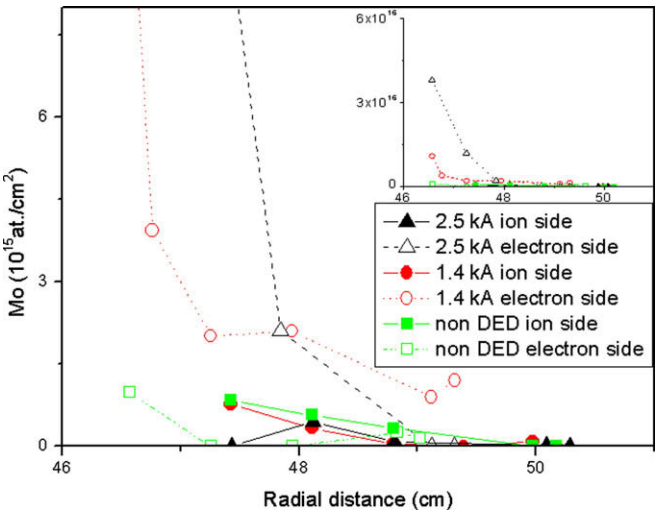

Fig. 5. Molybdenum deposits for three different plasma conditions. The symbols correspond to those in Figs. 3 and 4.

C/D ratio is at an average of about 2 for the all exposed points with a spread from 0.7 to 10 with most points between 1 and 4 indicating that the deuterium is largely co-deposited along with deuterium as expected.

Fig. 5 displays the measured Mo deposits on the sample surfaces. The metal was verified as Mo by particle induced X-ray emission. The scale is given in at./cm^2 since this probably is molybdenum sputtered from the slits of the housing and not deposits from the plasma. Besides the observed molybdenum, other metals were also detected, in particular Fe at an average of 6×10^{14} at./cm^2. The concentration of iron and molybdenum is correlated. This can be interpreted as a common source of these metals, probably the FRP housing. Mo and Fe are also present on the unexposed samples in low quantities (1×10^{14} and 0.5×10^{14} at./cm^2). The detection limits for the two metals depend on experimental conditions, such as pile-up, and are in the same range as what was measured on the unexposed samples.

If the maximum detected concentration of Mo actually had been present as an impurity in the plasma, this would have had been clearly observed in the plasma characteristics. Spectroscopic data from the discharges confirm that Mo are present in the plasma only when the probe is at the sampling position. Mo is most likely sputtered from the slit edges in the housing of the probe by the high deuterium-flux, or the main impurity carbon. Considering that the physical sputtering yield of Mo by C is calculated to be more than 100 times that of deuterium at relevant energies [13] carbon is the likely candidate. Calculations [4], for conditions prior to the DED installation, show that multiple charged carbon species dominates the carbon flow making an induced sheath potential extra important. The suggestion that carbon is the main source of sputtering appears to be contradicted by the results in Fig. 3, where a decrease in carbon deposition corresponds to an increase of molybdenum deposition in Fig. 5. At the same time a decrease in deuterium deposition is also observed in Fig. 4. One plausible explanation is that the increased Mo deposition may have affected the carbon and deuterium retention.

4. Conclusions

In the present study the fast reciprocating probe was used to capture deposits during plasma discharges in TEXTOR. The impact on plasma transport in the plasma edge by the dynamic ergodic divertor was investigated for three different conditions namely non-DED, low perturbation DED and high perturbation DED.

It was demonstrated that the fast reciprocating probe is useful for carbon and deuterium measurements in the scrape-off layer at pump-out conditions. The e-folding lengths found for the unperturbed case of deuterium agrees well with the measured values prior to installation of the DED. For perturbed shots, differences in the net deposited rates was found but only small difference in e-folding lengths.

Acknowledgements

Financial support from Swedish Science Research Council (VR) made this work possible. Dr. Wolfgang Biel, is acknowledged for assisting with spectroscopic data and Professor U. Karlsson and his group for their engagement and valuable comments to this work.

References

[1] B. Emmoth, M. Rubel, H. Bergåker, P. Wienhold, J. Winter, J. Nucl. Mater. 162 (1989) 409.
[2] I. Gudowska, H. Bergsåker, B. Emmoth, P. Wienhold, M. Rubel, J. Nucl. Mater. 176 (1990) 363.
[3] M. Rubel, F. Waelbroeck, H. Bergåker, P. Wienhold, B. Emmoth, J. Nucl. Mater. 161 (1989) 153.
[4] B. Emmoth, P. Wienhold, M. Rubel, B. Schweer, R. Zagórski, J. Nucl. Mater. 313 (2003) 729.
[5] M.W. Jakubowski, S.S. Abdullaev, K.H. Finken, the TEXTOR Team, Nucl. Fusion 44 (2004) S1.
[6] S.S. Abdullaev, K.H. Finken, M.W. Jakubowski, S.V. Kasilov, M. Kobayashi, D. Reiter, A.M. Runov, R. Wolf, Nucl. Fusion 43 (2003) 299.
[7] O. Schmitz, J.W. Coenen, H. Frerichs et al., J. Nucl. Mater. 390–391 (2009) 330.
[8] R.A. Langley, Radiation Effects and Tritium Technology for Fusion Reactors, 1976.
[9] D.A. Bromley, E. Almqvist, H.E. Gove, A.E. Litherland, E.B. Paul, J. Fergusson, Phys. Rev. 105 (1957) 957.
[10] O. Schmitz et al., J. Nucl. Mater. 363 (2007) 680.
[11] G. Telesca et al., in: Thirty Fourth EPS Conference on Plasma Phys. ECA, vol. 31F, 2007, p. P-1.045.
[12] H. Bergsåker, M. Rubel, B. Emmoth, P. Wienhold, J. Nucl. Mat. 162 (1989) 593.
[13] W. Eckstein, Calculated Reflection and Range Values, Max-Planck-Institut für Plasmaphysik, IPP9/132, 2002.