EUROFUSION WPMST1-PR(15) 14525

A Garcia-Carrasco et al.

Fuel removal from probe surfaces by ion cyclotron wall conditioning in ASDEX Upgrade

Preprint of Paper to be submitted for publication in
Nuclear Fusion

Fuel removal from probe surfaces by ion cyclotron wall conditioning in ASDEX Upgrade

A. Garcia-Carrasco[1], P. Petersson[1], T. Schwarz-Selinger[2], T. Wauters[3], D. Douai[4],
V.Bobkov[2], K. Krieger[2], A. Lyssoivan[3], V. Rohde[4], M. Rubel[1] and ASDEX Upgrade Team[4]

[1]*Department of Fusion Plasma Physics, Royal Institute of Technology (KTH), Teknikringen 31, 100 44 Stockholm, Sweden*
[2] *Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, D-85748 Garching, Germany*
[3] *Laboratory for Plasma Physics, ERM/KMS, 1000 Brussels, Belgium*
[4] *CEA, IRFM, F-13108 St-Paul-Lez-Durance, France*

E-Mail: alvarogc@kth.se

Abstract. Ion cyclotron wall conditioning (ICWC) is envisaged to contribute to mitigate fuel retention in ITER. The purpose of this study was to assess the efficiency of ICWC in removal of deuterium from plasma-facing components. A set of pre-characterized tungsten probes with co-deposits from the TEXTOR tokamak was exposed in ASDEX Upgrade to 60 seconds of ICWC discharges in hydrogen. The change of deuterium content before and after exposure to H_2-ICWC was measured by nuclear reaction analysis, while the deuterium outgassing characteristics of the co-deposits was determined with thermal desorption spectrometry. Either reduction by 20 - 40 % or no significant reduction of deuterium content was observed depending on the original sample composition. It was also found that ICWC operation led to preferential removal of deuterium trapped at temperatures below 600 °C in co-deposits formed under tokamak discharges. For the first time, material analysis techniques have been applied to study the effect of ICWC on probe surfaces in an all metal wall machine.

Keywords: *ICWC, Erosion-deposition, fuel removal, ion beam analysis, ASDEX Upgrade*

1. Introduction

In ITER, wall conditioning will play an important role by contributing to the following tasks: (i) assist plasma start-up after venting or disruptions, (ii) improve plasma performance by reducing desorption of impurities from the wall, and (iii) mitigation of tritium inventory in plasma-facing components (PFC). One of the challenges in the development of wall conditioning procedures for ITER is the nearly permanent presence of strong magnetic fields, which rules out the use of glow-discharge cleaning for inter-shot wall conditioning. This calls for testing alternative techniques compatible with magnetic fields, such as ion cyclotron wall conditioning (ICWC) [1, 2].

ICWC is based on radio-frequency (RF) generated low-temperature plasmas. RF power is absorbed in the plasma through a combination of non-resonant electron heating and resonant ion heating [3, 4]. Gas composition is chosen according to the intended effect on the wall surface state, for example, hydrogen isotopes are used to change the isotopic ratio of the wall [5, 6]. ICWC has been tested and studied in several tokamaks: Tore Supra [7], TEXTOR [8], JET [9], ASDEX Upgrade [10], HT-7 [11], EAST [12], KSTAR [13], and stellerators: WT-AS [14], LHD [15], URAGAN-3M [16]. Typical ICWC discharge conditions are: heating power between 10^4 - 10^5 W, neutral pressure in the range 10^{-3} - 10^{-2} Pa and toroidal magnetic field between 0.2 - 4 T. ICWC is still under development, therefore a wide range of experimental conditions are usually applied to explore the optimal operational window for a given fusion device and to have a comprehensive data base for ITER.

As stated above, the objective of ICWC is the removal of fuel and impurities from the first wall. To carry out this task efficiently, a better understanding of the interaction between the conditioning plasma and the wall is necessary. The most direct way to address this point is the exposure of pre-characterised probes to ICWC plasma followed by the ex-situ analyses of such samples. Up to date, such studies have been performed only in carbon-wall machines, where carbon-hydrogen chemistry is decisive for material migration [17 - 19]. To provide more ITER-relevant results, experiments in metal-wall machines have been undertaken. The aim of this work is to determine the efficacy of ICWC in fuel removal from tokamak co-deposits. The experiment was carried out in ASDEX Upgrade (AUG), a medium-size tokamak with tungsten-coated PFC.

2. Experiment

Six polycrystalline tungsten samples with co-deposits formed under different types of plasma conditions in the TEXTOR tokamak were exposed in AUG to 6 discharges of 10 seconds of H_2-ICWC plasma. The samples (20 x 20 x 3 mm^3) were mounted on a stainless steel holder and inserted into the AUG vessel at the same radial position as the antenna limiter using a manipulator in the outer mid-plane.

Figure 1 shows a picture of the probes mounted on the holder before exposure in AUG. The coloured pattern indicates the presence of co-deposits, which consisted of carbon, nitrogen (^{14}N and ^{15}N), oxygen, boron and metals (Ni, Cr, Fe) from the Inconel liner. The oval-shaped marks (about 1 x 4 mm^2) in some of the samples were produced during the pre-characterization by means of ion beam techniques. The numbering of probes in figure 1 will be used throughout the presentation of results.

During the H_2-ICWC discharges the toroidal magnetic field was 2 T, the antenna frequency was 30 MHz and the neutral pressure was at the level of 2.3 x 10^{-2} Pa. The generated power at the antennas ranged from 40 kW to 130 kW. This set of conditions was a compromise to satisfy all experimental goals because, besides the probe-surface exposure, the experiment had also other scientific objectives, e.g. optimization of ion cyclotron resonance frequency (ICRF) plasma production and plasma characterization.

The isotopic composition of the plasma was monitored with visible spectroscopy of $H\alpha$ and $D\alpha$ lines. Deuterium content in the tungsten probes was measured with nuclear reaction analysis (NRA) using a 2.8 MeV $^3He^+$ beam at the 5 MV Tandem Accelerator Laboratory, Uppsala University. Protons produced in the nuclear reaction $D(^3He,p)^4He$ were detected at a scattering angle of 165° with a silicon solid state detector. Deuterium outgassing from the samples was characterized with thermal desorption spectrometry (TDS) in the quartz tube of the TESS device [20]. The temperature of the tubular oven was increased linearly with a temperature ramp of 15°C per minute up to 1050 ºC. Signals from 21 different mass channels between 1 amu/q and 44 amu/q were recorded as a function of time. Because of possible interference with He implanted during ICWC discharges in TEXTOR mass channel 4 amu/q was discarded from being a good measure for deuterium desorption. Signals at mass 3 amu/q were used instead. After each desorption run the signal background was determined by removing the sample from the hot part of the quartz tube and repeating the temperature ramp under otherwise identical conditions. Absolut quantification was conducted as described in [21] showing reasonable agreement with NRA measurements. Temperature calibration was done by a type-K thermocouple placed underneath the samples.

2.1 Samples history

The tungsten probes were selected from a previous experiment in TEXTOR because of the following reasons: (i) well characterized tokamak co-deposits, and (ii) exposure under different plasma conditions. Samples 1, 2, 2A, and 3 were exposed in TEXTOR to 31 tokamak discharges (in total 124 s) fuelled with deuterium, heated by hydrogen neutral-beam injection (I_p = 350 kA, B_t = 2.25 T, n_e = 3 x 10^{19} m^{-2}) and seeded with ^{15}N. Samples 4, 4A, 5 and 6 were exposed first to discharges described above, and then to ICWC plasma in TEXTOR: 315 s of deuterium pulses (p = 2 x 10^{-2} Pa), and then 112 s He discharges (p = 4 x 10^{-2} Pa). The toroidal magnetic field was set at 0.23 T and the generated power at the antennas was either 50 or 100 kW. For both types of discharges, samples were mounted on a roof-shaped holder and inserted from the top of the vessel using a transfer system. Samples 2A and 4A differ from their counterparts in that they were not exposed to plasma in AUG after the TEXTOR experiment.

The surface composition of tungsten probes with co-deposits from TEXTOR differed significantly from one sample to another, as determined by ion beam analysis. This difference was related to plasma conditions and sample location during exposure. A concise summary of plasma conditions is given in Table 1, while more details on the experiment in TEXTOR can be found in [19].

3. Results

Figure 2 shows the evolution of the hydrogen-to-deuterium ratio in the main chamber of AUG during the exposure of the tungsten probes to H_2-ICWC. After the first discharges, the ratio of hydrogen-to-deuterium in the plasma reaches a steady value of about 2. The dilution of hydrogen in the plasma due to the continuous release of deuterium from the wall could have an impact on the efficiency of deuterium removal from the probes.

The relation between deuterium concentration on the samples before and after exposure to H_2-ICWC in AUG is shown in Figure 3. Each sample was analysed with NRA at four different points. The relative uncertainty of the measurement is about 10 % with the exception of Samples 1 and 3, in which the relative uncertainty is about 50 % because deuterium content was close to detection limit (1×10^{15} cm^{-2}). The main results are summarised by the following: (i) reduction of deuterium content by about 20 to 40 % in Samples 4, 5 and 6, (ii) no significant change of deuterium content in Sample 2, and (iii) low deuterium content (close to detection limit) in Samples 1 and 3 both before and after plasma exposure.

Taking into account a small size of the target holder (see figure 1) one may assume that all probes were exposed in AUG under the same conditions, i.e. particle dose and energy. Therefore, the significant differences between the samples in the fuel removal efficiency by ICWC are most probably attributed to the plasma conditions under which co-deposits were formed in TEXTOR. TDS measurements were performed to determine differences in the properties of co-deposits by studying the desorption characteristics of deuterium. Figure 4 shows the signal of mass channel 3 amu/q (hydrogen deuteride) as a function of temperature. Four samples were examined: 2, 2A, 4 and 4A (see table 1 for samples history). All data have been normalized to enable comparison and interpretation of results because deuterium content differed significantly from sample to sample.

In general, the normalized desorption features look very similar for all samples: desorption begins at a temperature above 200°C and starts to drop well before the oven reaches the maximum temperature. The maximum desorption rate of deuterium from samples exposed only to NBI-heated discharges (Samples 2, 2A) occurs at higher temperature (775°C) than for those exposed to both NBI-heated and D_2/He-ICWC discharges (Samples 4, 4A, 720°C).

This is most probably related to higher energy of particles at the plasma edge during tokamak operation compared to ICWC.

The lower deuterium desorption rate of Sample 2 compared to Sample 2A below 600 °C suggests that H_2-ICWC operation led to a preferential removal of deuterium trapped in that temperature range. Therefore, differences observed in fuel removal between samples are probably related to the fact that part of the deuterium retained under tokamak discharges is less accessible by ICWC than the deuterium retained under ICWC operation. Samples 4 and 4A show almost identical normalized desorption characteristics because they had already been exposed to ICWC plasma before the AUG experiment.

4. Concluding remarks

Tungsten probes exposed to ICWC plasma in AUG were examined by material analysis techniques to determine deuterium removal. This is the first experiment of the kind and represents a step forward towards a better understanding of how ICWC plasmas affect the first wall in metallic machines such as ITER.

Based on this single experiment it would be risky to draw far reaching conclusions regarding fuel removal efficiency. It has been shown that up to 40 % of deuterium could be removed from deuterium-rich deposits. However, the conditioning plasma contained significant amounts of deuterium (see figure 2) and the exposure time was only 60 s. Conditioning activities in ITER will span several hours, leading to isotopically more clean hydrogen plasmas and much higher ion fluencies to the wall. Lessons from this first experiment will serve for future activities in AUG carried out during longer exposure times.

Another issue to address in future experiments is the impurity removal from co-deposits, for instance nitrogen used for edge cooling. In this particular case co-deposits with nitrogen-15 marker would be useful. This, however, requires highly uniform layers on smooth substrates to eliminate or at least strongly reduce the sources of errors in surface analysis.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The work has been partly funded by the Swedish Research Council (VR) through contract no. 621-2009-4138.

5. References

[1] M. Shimada et al., J. Nucl. Mater. 415 (2011) S1013

[2] D. Douai et al., J. Nucl. Mater. 463 (2015) 150

[3] A. Lyssoivan et al., J. Nucl. Mater. 415 (2011) S1029

[4] D. Douai et al., J. Nucl. Mater. 415 (2011) S1021

[5] G. Sergienko et al., J. Nucl. Mater. 390-391 (2009) 979

[6] G. L. Jackson et al., Nuclear Fusion 30 (1990) 2306

[7] E. Gauthier et al., J. Nucl. Mater. 241-243 (1997) 553

[8] A. Lyssoivan et al., J. Nucl. Mater. 363-365 (2007) 1358

[9] T. Wauters et al., J. Nucl. Mater. 463 (2015) 1104

[10] A. Lyssoivan et al., J. Nucl. Mater. 337 (2005) 456

[11] Z. Yan-Ping et al., Chinese Physics Letters 337 (2005) 456

[12] J. Hu et al., J. Nucl. Mater. 376 (2008) 207

[13] S. H. Hong et al., Nucl. Fusion 51 (2001) 103027

[14] R. Brakel et al., J. Nucl. Mater. 290-293 (2001) 1160

[15] N. Ashikawa et al., Plasma and Fusion Research 6 (2011) 2402138

[16] A.V. Lozin at al., Plasma Phys. Reports 39 (2013) 624

[17] T. Wauters et al., Nucl. Fusion 53 (2013) 123001

[18] A.G. Carrasco et al., Phys. Scr. T159 (2013) 014017

[19] A.G. Carrasco et al., J. Nucl. Mater. 463 (2015) 688

[20] E Salançon at al., J. Nucl. Mater. 376 (2008) 160

[21] P Wang et al., Nucl. Instr. and Meth. 300 (2013) 54

Figures:

Figure 1: Tungsten probes installed in the holder before exposure to H_2-ICWC in AUG.

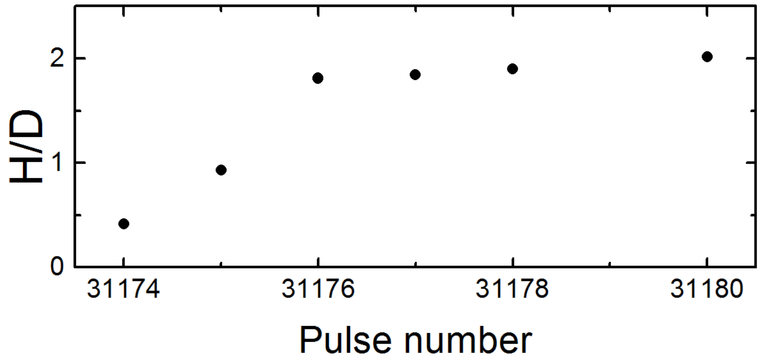

Figure 2: Shot-to-shot evolution of the hydrogen-to-deuterium ratio as measured by visible spectroscopy in the AUG main chamber comparing Hα (656.3 nm) and Dα (656.1 nm) lines.

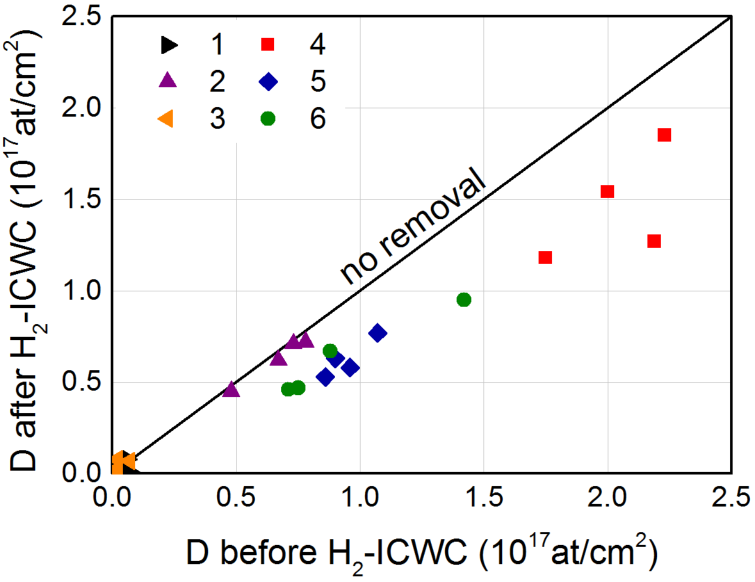

Figure 3: Relation between deuterium content on the samples before and after H_2-ICWC in AUG.

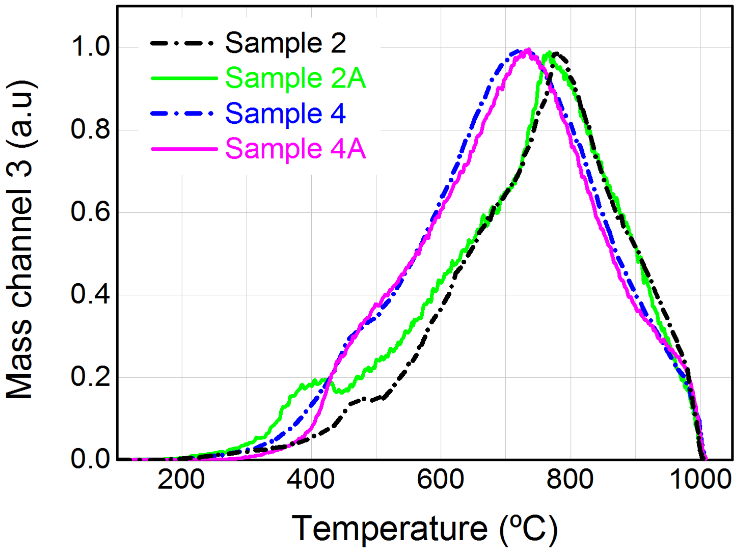

Figure 4: Normalized signal from mass channel 3 amu/q as a function of sample temperature.

Tables

Table 1: Summary of sample exposure conditions. NBI stands for tokamak discharge heated by neutral beam injection.

Samples	TEXTOR	ASDEX-Upgrade
1, 2, 3	NBI	H_2-ICWC
2A	NBI	
4, 5, 6	NBI + D_2/He-ICWC	H_2-ICWC
4A	NBI + D_2/He-ICWC	