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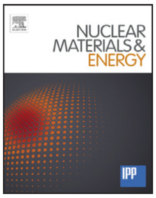

# Investigation of probe surfaces after ion cyclotron wall conditioning in ASDEX upgrade

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## ABSTRACT

For the first time, material analysis techniques have been applied to study the effect of ion cyclotron wall conditioning (ICWC) on probe surfaces in a metal-wall machine. ICWC is a technique envisaged to contribute to the removal of fuel and impurities from the first wall of ITER. The objective of this work was to assess impurity migration under ICWC operation. Tungsten probes were exposed in ASDEX Upgrade to discharges in helium. After wall conditioning, the probes were covered with a co-deposited layer containing D, B, C, N, O and relatively high amount of He. The concentration ratio He/C+B was 0.7. The formation of the co-deposited layer indicates that a fraction of the impurities desorbed from the wall under ICWC operation are transported by plasma and deposited away from their original location.

## 1. Introduction

Wall conditioning will play an important role in ITER by: (i) assisting plasma start-up after venting or disruptions, (ii) improving plasma performance by reducing desorption of impurities from the wall, and (iii) mitigating fuel inventory in plasma-facing components (PFC). One of the challenges in the development of wall conditioning methods for ITER is the nearly permanent presence of strong magnetic fields. This excludes the use of glow-discharge cleaning for inter-shot wall conditioning. As a consequence, it is necessary to develop and test alternative techniques compatible with magnetic fields, such as ion cyclotron was conditioning (ICWC) [1, 2].

ICWC is based on low-temperature plasma produced by radio-frequency (RF) waves. The RF power is absorbed in the plasma through a combination of non-resonant electron heating and resonant ion heating [3, 4]. Typical ICWC discharge conditions are: heating power of $10^4$–$10^5$ W, electron densities of $10^{16}$–$10^{17}$ $\mathrm{m}^{-3}$ and toroidal magnetic field of 0.2–4 T. A wide range of experimental conditions are usually applied to explore the optimal operational window for a given fusion device and to collect a comprehensive data base for ITER. As a comparison, typical parameters during an H-mode discharge at ASDEX Upgrade are: heating power of $10^7$ W, electron densities of $10^{19}$–$10^{20}$ $\mathrm{m}^{-3}$ and magnetic field of 2.5 T.

Gas composition during the wall conditioning discharge is chosen according to the intended effect on the wall surface state. Hydrogen isotopes are used to control the fuel content in the wall by isotopic exchange and chemical erosion of carbon co-deposits. Alternatively, inert species such as helium are selected to remove impurities from PFC by ion-induced desorption and physical sputtering [5, 6]. ICWC has been tested in several tokamaks: Tore Supra [7], TEXTOR [8], JET [9], ASDEX Upgrade [10], HT-7 [11], EAST [12], and KSTAR [13].

The objective of ICWC is the removal of fuel and impurities from the first wall. The most direct way to investigate the efficiency of the technique is the exposure of pre-characterised

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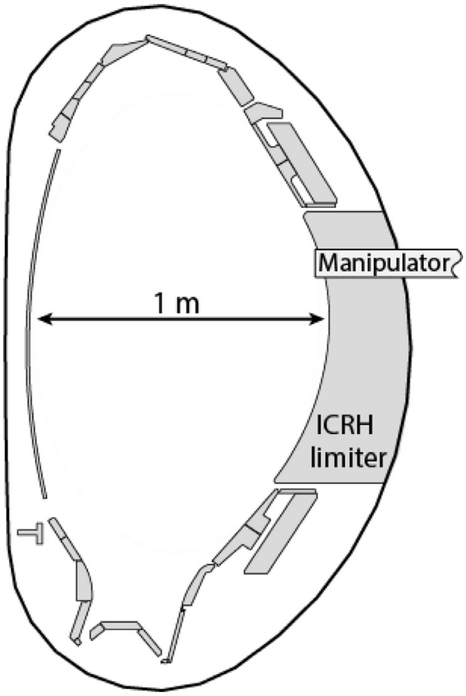

**Fig. 1.** Cross section of the AUG vessel showing the location of the mid-plane manipulator.

probes to ICWC plasmas, followed by ex-situ surface analyses of the probes. Up to date, such studies have been performed only in carbon-wall machines, where carbon-hydrogen chemistry is decisive for material erosion and migration [14–16]. The objective of this work was to assess impurity migration under ICWC operation in ASDEX Upgrade, a metal-wall machine.

## 2. Experimental

ASDEX Upgrade (AUG) is a medium-size tokamak with tungsten-coated tiles made of carbon-fibre composites. Boronization is regularly performed in AUG to increase plasma performance. A boronization campaign was performed 4 days before the experiment presented here. A set of tungsten samples was exposed to ICWC in helium plasma (He-ICWC) during 190 s: 19 discharges of 10 s each. For exposure, the samples were mounted on a specially designed holder and inserted into the AUG vessel using a manipulator in the outer mid-plane, as shown in Fig. 1. The holder was made of tungsten-coated graphite and it was equipped with two built-in Langmuir probes to measure ion fluxes. The Langmuir probes were placed in the front surface of the holder, right next to the samples. Fig. 2 shows the samples mounted on the holder before exposure to plasma. During discharges, the samples were inserted 2 cm into the plasma with respect the antenna limiter. The neutral pressure was at the level of $1–5 \times 10^{-2}$ Pa and the generated power at the two operated antennas was 210 kW. The toroidal magnetic field and antenna frequency were set at 2 T and 30 MHz respectively.

The exposed probes were examined with ion beam analysis (IBA) methods. All analyses were performed using a 5 MV Tandem Accelerator at Uppsala University. Helium and deuterium concentrations were determined by elastic recoil detection analysis (ERDA) using a 10 MeV $^{28}Si^{3+}$ beam. The recoiled atoms were measured at a scattering angle of 37° with a solid state silicon detector. The detector was covered with a 6 µm Mylar foil to eliminate the signal from recoiled species heavier than helium.

Concentrations of heavier species such as carbon or boron were measured using time-of-flight ERDA with a 36 MeV $^{127}I^{8+}$ beam.

**Fig. 2.** Samples installed in the manipulator before exposure to He-ICWC.

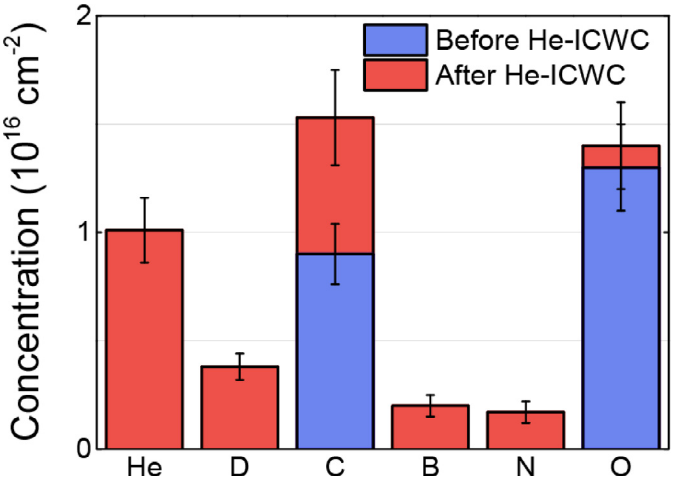

**Fig. 3.** Concentration of impurities on tungsten samples before and after He-ICWC.

Flight time and energy of the recoiled atoms were measured at a scattering angle of 45° using a newly constructed telescope. The time-of-flight detectors, located at 42.5 cm and 82.5 cm respectively from the sample position consist of 5 µg/cm$^2$ carbon foils with 2 micro-channel plates each, in chevron stack configuration. For the energy detection, a gas ionization chamber is used, with isobutene ($C_4H_{10}$) as working gas, normally at a pressure of 30 mbar [17].

Optical spectroscopy was used to monitor the relative concentration of fuel species in the plasma: hydrogen (656.3 nm) and deuterium (656.1 nm). A high resolution spectrometer was required to differentiate between hydrogen isotope lines. The detector exposure time was 100 ms. Photon fluxes were averaged over the time window from 4.0 to 4.5 s of the discharge time.

## 3. Results and discussion

He-ICWC resulted in the formation of a co-deposited layer on the exposed tungsten substrates. The co-deposited layer was very similar for all samples and its composition is presented in Fig. 3. There are small amounts of helium, deuterium, carbon, boron, nitrogen and oxygen. The impurity concentrations range from $2–15 \times 10^{15}$ cm$^{-2}$. Carbon, boron and nitrogen are typical impurities in AUG. Carbon originates mostly from damaged coatings on the tiles, boron is regularly used to condition the walls and nitrogen is seeded during high-performance discharges to increase radiation power in the divertor. An important constituent of co-deposits is

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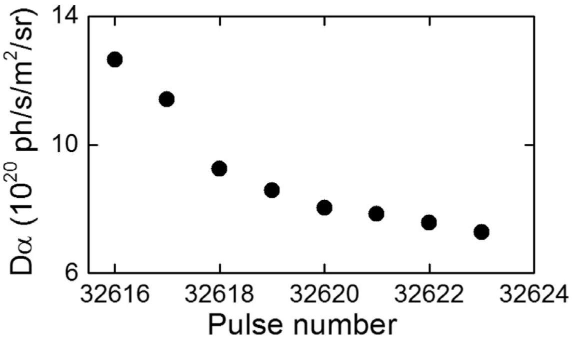

**Fig. 4.** Evolution of D$\alpha$ photon flux during He-ICWC discharges.

helium, about $1 \times 10^{16}$ cm$^{-2}$. The analyses clearly prove that this chemically inert gas is not instantly released from the probes after ICWC. This result confirms earlier findings [18–20] about the helium retention. The point is that the concentration measured after experiments in He-ICWC is relatively high, e.g. the concentration ratio of He/C+B = 0.7, while the ratio of D/C+B equals only 0.2. Even though neither carbon nor boron should be present in ITER but rather is consequence of operating in AUG, the general trend of relative low deuterium concentration compared to helium in the co-deposits on a tungsten surface is positive. The ion fluence measured by the Langmuir probes located next to the samples was on average at the level of $6 \times 10^{17}$ cm$^{-2}$. The temperature of the holder was monitored using an infra-red camera. The temperature did not increase by more than 20° during the discharges.

The evolution of the D$\alpha$ photon flux in the main chamber of AUG during He-ICWC discharges is shown in Fig. 4. There is a clear reduction of deuterium concentration in plasma during ICWC operation, indicating deuterium removal from plasma-facing components. This might seem to contradict surface analyses results, which report the formation of a co-deposited layer containing deuterium on the surface of the tungsten samples. However, each measurement provides a different type of information: global and local. The combined picture is that during wall conditioning, deuterium and other impurities are desorbed from the wall under helium bombardment. Part of the desorbed species are pumped out of the vessel, while the other part is ionized by electron impact, transported by plasma and deposited elsewhere in the wall.

Wall components are under a dynamic competition between erosion and deposition. There is an equilibrium concentration at which impurity erosion and deposition balance each other. During wall conditioning, impurities are preferentially eroded from regions with higher concentrations than the equilibrium level and preferentially deposited on regions with lower concentrations than the equilibrium level. From previous experiments [4] most of the plasma wall interactions have been seen at the low field side i.e. in the region of the exposure for this experiment. The conclusion is that under ICWC operation, wall impurities are both removed from the vessel and spread out across the wall.

## 4. Concluding remarks

Tungsten probes were exposed to ICWC plasma in AUG and examined by surface analysis techniques to assess material migration. This is the first experiment of the kind performed in a metal-wall machine and represents a step forward towards a better understanding of the impact of ICWC operation on plasma-facing components. A combination of local measurements (probe surface analysis) and global measurements (optical spectroscopy) have been applied to study material migration under wall conditioning. It is complex to extrapolate results to ITER because the presence of carbon and boron in AUG plays a dominant role in the transport and co-deposition of material. However, all present-day machines have sources of carbon, even those with metal walls such as JET [21].

An important contribution of this work is related to the detection relatively high content of He in deposits (He/C+B = 0.7). One may tentatively suggest that He replaces some fuel species in the deposited layers on the machine wall. It is not chemically bound but is still retained a couple of weeks after the ICWC experiment, i.e. time interval between the exposure in AUG and analyses. It has been measured earlier [22] that He is desorbed from co-deposits after long storage in air, but in those layers the relative He contents were much smaller. However, the question is, how efficient is the release of helium after ICWC in a tokamak. Therefore, in future experiments one would propose to examine carefully a start-up operation of tokamak discharges following ICWC.

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