PLASMA PHYSICS AND APPLICATIONS

CHARACTERISATION OF TUNGSTEN NITRIDE LAYERS AND THEIR EROSION UNDER PLASMA EXPOSURE IN NANO-PSI*

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Abstract. The properties of tungsten nitride thin films deposited by both reactive RF-magnetron sputtering from tungsten targets in Argon/N₂, and RF generated nitrogen ions bombardment of previously sequentially deposited tungsten layers have been investigated. Films exhibited smaller erosion than pure tungsten in Argon plasmas at NANO-PSI expanding thermal plasma device.

Key words: Tungsten nitride, tungsten, nitrogen, erosion, RF-magnetron sputtering, ITER, multilayer characterization, linear plasma device, NANO-PSI.

1. INTRODUCTION

Transition from carbon-based materials to tungsten for the divertor target material in fusion devices renders the injection of controlled impurities in the edge plasma mandatory to radiatively cool the divertor plasma in order to reduce the

walls damage and erosion from the plasma heat loads. Different noble gases like Ne and Ar have been tested, but the best results so far have been obtained with N₂ seeding in the ASDEX Upgrade tokamak [1]. In these experiments also an overall improvement of the plasma confinement was detected due to a strongly reduced power load to divertor walls and the total suppression of W influx into the plasma [1, 2]. These effects have been ascribed to the expected lower electron temperature in the divertor, but also to the development of tungsten nitrides films at the surface of the W tiles reducing the W sputtering. Furthermore, tungsten nitrides, in particular W₂N, have been widely studied as diffusion barriers for interconnecting metallization in microelectronics due to their extreme hardness, good chemical resistance, high electrical conductivity and high melting point [3–8].

**In-situ** nitriding by He/N₂ glow discharge has been proposed for W impurity reduction in the JET and ASDEX Upgrade tokamaks. However, the tungsten nitride layers created in this way are only a few nm thick, which are insufficient to last during long pulses or withstand heavy heat loads like these expected during Edge-Localized Modes (ELMs) in ITER. These results suggest that W tiles coated with tungsten nitride films could be an alternative for coating the plasma facing materials in a fusion reactor. In order to study their viability, thin films of WNₓ were deposited on Si and W substrates using two different techniques. The first one consists on reactive RF-magnetron sputtering (RMS) from pure W targets in an Ar/N₂ mixture. The second deposition method (sequential deposition and nitriding, SDN) consists on repeating the following sequence (cycle): deposition of a thin layer of pure W or tungsten nitride (in a regular magnetron sputtering, MS, or in a RMS process) followed by exposure to a RF generated N₂ plasma [9].

The properties of the films have been characterised by different techniques like Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM), X-Ray Diffraction (XRD), X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Microscopy (AES) [3–8]. Finally the deposited films have been subjected to high flux argon plasmas in the NANO-PSI expanding thermal plasma device to directly compare the erosion between the tungsten nitride thin films and the bare tungsten substrate.

### 2. EXPERIMENTAL

Since the sequential deposition setup has been presented previously [9], only a brief description will be given here. The experimental system is presented schematically in Fig. 1. It is based on two orthogonally mounted plasma sources powered with 13.56 MHz RF energy: a magnetron for tungsten deposition and a second one (Plasma Enhanced Chemical Vapour Deposition, PECVD type) for nitrogen bombardment. The sample holder can be rotated *in situ* (using a computer-controlled stepper motor), allowing alternative exposure of the substrate to both
Before deposition the vacuum chamber was first evacuated to a base pressure of $5 \times 10^{-3}$ Pa. Then the silicon (110 oriented) substrates were cleaned in argon RF discharge for 15 min using the PECVD plasma source, while the tungsten magnetron target was pre-sputtered for 5 min with a shutter placed between the target and the substrate. The target-substrate distance is 8 cm and the substrate can be biased up to $-200$ V. Supplementary, both plasma processes are monitored by Optical Emission Spectroscopy (OES). Two deposition procedures were implemented on the previously presented setup to deposit different types of tungsten nitride films:

- **Reactive Magnetron Sputtering (RMS):** the W target is sputtered in an Ar/(10%)N$_2$ plasma at a pressure of 0.9 Pa and 47 W RF power. These experimental conditions were previously optimized to obtain films with low stress levels [10]. The deposition rate was 8.8 nm/min. To avoid target poisoning one of the optical emission lines ($\lambda = 400.88$ nm) of WI was continuously monitored by OES.

- **Sequential Deposition and Nitriding (SDN):** it was performed by depositing first a thin layer, 3 nm or 10 nm, of tungsten (or tungsten nitride) in a MS (or RMS) based process in similar conditions, pressure and power, than previous procedure. The deposition rate for pure tungsten is 8.6 nm/min, very similar than for RMS. Secondly the substrate is rotated 90° to face the second plasma source and then argon is pumped out and nitrogen is let in. Pure N$_2$ RF plasma is created at a pressure of 0.9 Pa and 80 W RF power during 1 hour or 10 minutes in case of RMS tungsten nitride. A $-200$ V bias is applied to the substrate in order to increase ion kinetic energy and thus the nitrogen implantation range. The measured ion flux is $1.05 \times 10^{19}$ m$^{-2}$s$^{-1}$, so that nitrogen atom fluences of $7.6 \times 10^{22}$ m$^{-2}$ for 1h and $1.3 \times 10^{22}$ m$^{-2}$ for 10 min at mostly 100 eV bombardment energy are derived. At these fluences the surface is expected to be saturated as the maximum N areal density has been calculated in the order of $\sim 10^{20}$ m$^{-2}$ [1].
The substrate temperature during the deposition is estimated to be around 60–80 °C due to plasma heating. 99.9999% purity Ar and N$_2$ gases were used. The film thickness and erosion were measured by a Dektak 150 Veeco profilometer. The cross section SEM measurements were performed using a FEI model Inspect S scanning electron microscope. The depth distribution of the atomic composition of the tungsten nitride layers was investigated by AES using a PHI SAM 545 spectrometer. For electron excitation a primary electron beam of 3 keV and 1 μA, with a diameter of 40 μm was used. During depth profiling the samples were sputtered by two symmetrically inclined Ar ion beams of 1 keV on rotating samples in order to improve depth resolution [11]. The sputtering rate measured on a PVD WN$_{0.5}$ layer was 1.3 ± 0.2 nm/min under similar experimental conditions, and it will be used as a reference for the present AES measurements. The relative sensitivity factors (RSF) provided by the instrument manufacturer were used to calculate the concentrations. Relative error in AES results on elemental concentration is about 20%. The crystallinity was investigated by XRD using a Panalytical X'Pert MRD PRO system. The formation of nitride phases was studied by XPS in a VG ESCA 3 MKII using monochromated Al K$_\alpha$ radiation (1486.6 eV) or in a ESCAPROBE P with a non-monochromatic Mg K$_\alpha$ (1253.6 eV) source with a hemispheric analyser Omicron EA125. Cross section TEM samples were prepared by gluing with epoxy resin two samples face to face and after subjected to a mechanical thinning and ion milling. The images were taken in a 200 kV Philips Tecnai 20 TEM.

Finally some samples were exposed to pure argon plasmas in the Nano-PSI expanding thermal plasma device. A more extensive description can be found in [12]. Briefly, the plasma is generated by a cascaded arc source and expands into a spherical vacuum vessel with a base pressure of about $10^{-5}$ Pa. The sample holder is positioned in the center of the vacuum vessel, approximately 30 cm away from the nozzle of the plasma source. The device is operated in steady-state conditions at an argon ion flux of $\sim 10^{21}$ m$^{-2}$ s$^{-1}$ and a substrate bias of tens of volts. This results in a power density in the order of 10–20 kW/m$^2$, 2–3 orders of magnitude lower than expected in future nuclear fusion devices like ITER. Hence the applied power is only able to erode by sputtering in this device. The sample was water-cooled, and a temperature around 100ºC was measured continuously along the experiment by means of a thermocouple.

3. RESULTS

3.1. CHARACTERIZATION OF REACTIVE MAGNETRON SPUTTERING SAMPLES

SEM cross section image presented in Fig. 2 shows the compact columnar structure of the deposited layers, suggesting the good quality of the films for their application as first wall material in nuclear fusion devices.
Figure 3 presents the XRD patterns of the deposited W$_2$N and W thin films: it shows that the W$_2$N layers present a polycrystalline structure, with no W inclusions. The peaks of the W$_2$N phase are shifted to low angles giving a lattice constant of $a = 0.427$ nm, which dilates significantly in comparison with the standard $\beta$-W$_2$N phase ($a = 0.4126$ nm) [3–6]. The value of the mean crystallites size is 94 nm. A Williamson-Hall approach was used in order to remove the contribution of micro-strains from the peaks broadening.

The chemical bonding was analyzed by XPS, as is shown in Fig. 4. The N1s peak is related to nitride bonding and it is located at 397.9 eV of binding energy, in
the upper range of the usually reported values of 397.0–397.7 eV [1, 6, 7]. A small peak can be recognized at 400.3 eV which could be related to the absorbed N₂ [1]. In the W4f region of the spectrum, the two core levels W4f_{7/2} and W4f_{5/2} of W₂N at 33.5 eV and 35.6 eV (peaks denoted with A and B respectively) are identified. They are very close to other reported values for W₂N: 33.2 eV and 35.3–35.6 eV [6, 7]. In the upper part of binding energies of W4f region four smaller peaks (C, yellow and purple E and F), which can be associated with tungsten oxides, are identified [6, 7]. The most important impurities detected by XPS are carbon and oxygen, with concentrations around 15–20% and 8–12% respectively. The presence of these impurities is associated mainly with residual gases inside the deposition chamber.

XPS and AES analysis gives N/W ratios of 0.32 ± 0.06 and 0.37 ± 0.07 respectively, very close to stoichiometric 0.33. This fact corroborates the obtention
of pure W$_2$N. Finally, deposition of W$_2$N by RMS using a substrate bias of –200V was tested. It resulted in a lower deposition rate and a lower nitrogen content, even decreasing with depth, similar with the results previously reported by other authors [8]. This is probably due to an improved reaction of bombarding nitrogen ions with implanted N atoms.

3.2. CHARACTERIZATION OF SEQUENTIALLY DEPOSITED AND NITRIZED (SDN) SAMPLES

Cross section TEM image depicted in Fig. 5 shows the 3–5 nm thick layer of tungsten nitride (brighter) obtained after exposure of a W layer (dark) to a nitrogen plasma during 1 hour. The upper layer of pure W (30 nm thick) was applied at the end of the nitridation process as a protective layer. For obtaining thicker layers of this kind of tungsten nitrides the SDN method was implemented.

![TEM image of a W layer nitrided during 1 h. After the nitriding a 30 nm W layer was deposited in situ on top to protect the bombarded area from atmosphere, and to ease the identification in TEM.](image)

A similar tungsten nitride sample as used in Fig. 5, 10 nm W layer bombarded by a N$_2$ plasma covered with 5 nm of protective W, was analyzed by XPS after removing the protective layer (Fig. 6). After the nitrogen bombardment the layer thickness was 24 nm due to the impurities intake as will be seen later. The N1s peak, indicating the presence of a nitride is located at 397.5 eV, peak A in Fig. 4b; in agreement with reported values of 397.0–397.7 eV [1, 6, 7]. Supplementary, a small peak, probably related to trapped N$_2$ is detected at 399.7 eV. Regarding the W4f spectral region, the peaks A (31.8eV) and C (34.0eV) with the W4f$_{7/2}$ and W4f$_{5/2}$ core levels could be assigned to tungsten nitrides of different nature than the ones obtained by RMS [1, 6, 7]. Furthermore, peak B is close to 33.6 eV reported for metallic tungsten [3], and a small contribution from W$_2$N can be seen at peak D, 35.0 eV [6, 7]. Again, in the upper range of binding energies two peaks, E and
F, associated with tungsten oxides can be observed [6, 7]. All those peaks indicate a mixture of metallic tungsten, oxides, and probably both nitrides WN and W$_2$N. Finally, oxygen content deduced from the global XPS spectra is about 20%; also confirmed by AES measurements presented below. On the other hand, carbon content is too low to be easily quantified because of its chemical erosion by N ion bombardment.

Fig. 6 – XPS spectra of W 4f and N 1s obtained on plasma nitrided tungsten sample.

Whereas one step of deposition followed by nitriding results in a too thin film, 10 step SDN samples were prepared with 10 and 3 nm thick W layers, respectively. The SDN sample with 10 nm nitrided W layer resulted in a multilayer structure of roughly 5–6 nm of pure W and 7–9 nm of WN, as shown in Fig. 7, where AES depth profile is given. It was observed a significant contamination with
O, Fe and C mainly in the nitrided layers due to plasma nitriding. Most probably this is due to residual sputtering from chamber walls and substrate holder; it is not excluded also water or residual air contamination. This oxygen and impurities uptake is in accordance with the larger thickness of the nitrided layers sample compared to a blank one not subjected to plasma: 110 to 190 nm, as the density of tungsten and its nitrides is very similar and the films seem to be compact in SEM and TEM images. The N/W ratio in the nitrided layers varies between 0.32 and 0.7 in the uppermost layers, which have more impurities and fewer W. So perhaps each nitrided W layer is affected by the plasma during the following deposition-nitridation steps with a preferential sputtering of the lighter elements, increasing in this way the W ratio.

On the other hand 10 steps of 3 nm W layers resulted in a more homogeneous layer. It has the N/W ratio of 0.5–0.6 in the outermost layer decreasing quickly to 0.33–0.35 for the rest of the layer. Unfortunately, the impurities concentrations are even larger than for 10 nm W layers: 40–42% and 21–23% for oxygen and iron, respectively. This result, supported by the larger thickness (86 nm) of the nitrided multilayer structure, compared with the thickness (28 nm) of the W blank one (not subjected to plasma), confirms the contamination during the long (1 hour) plasma nitriding phase. The XRD analysis of the film compared to a blank one (10 deposition steps without plasma nitriding) in Fig. 8 shows a slight crystallinity with a possible combination of WN (100) and W$_2$N (111) peaks, although the N/W ratio points to a W$_2$N prevalence.
A 10 steps SDN of 2 nm W$_2$N layers deposited by RMS has also been done. As the surface already contents nitrogen, plasma nitriding time was shortened to 10 min in order to reduce contamination during the plasma nitriding. The AES depth profile and TEM images (not shown), reveal an almost homogeneous 50 nm plasma nitrided layer with a N/W ratio of 0.6. The nature of this nitrogen is probably more related to interstitial N than the formation of WN. As the sample holder was covered with W$_2$N due to the previous deposition, and the borders of the sample were discarded, the iron contamination was avoided. However, oxygen content remains relatively high, 29±3 %, signaling again an oxidation of the layer, difficult to avoid in our system.

### 3.3. CHEMICAL AND PHYSICAL EROSION OF W$_2$N FILMS IN DEUTERIUM AND ARGON

To test the sputtering enhanced by chemical reactions producing volatile compounds, usually called “chemical sputtering”, a W$_2$N film (deposited by RMS) is exposed to pure D$_2$ plasma. This was performed 30 min after the deposition of W$_2$N to allow the film to stabilize, with the substrate biased at –200V without breaking vacuum to avoid atmosphere contamination. Again, in order to protect the bombarded layer from the atmosphere 30 nm of W was deposited afterwards. The deuterium plasma treatment lasted for 1h and the estimated total D fluence was 5.6·10$^{22}$ m$^{-2}$. The W$_2$N film should not be physically eroded at the bombardment energies of this experiment, as its sputtering threshold is estimated to be over 250 eV. Nevertheless, it could be affected by chemical sputtering, i.e. a N preferential sputtering also aided by the possible chemical reaction to form ammonia which
desorbs from the surface [2]. This last point is confirmed by AES analysis in Fig. 9. Comparing the decrease of tungsten concentration with that of nitrogen in the part affected by the plasma (at 40 min in Fig. 9) the erosion thickness could be estimated. The nitrogen has been removed in the first $5.3 \pm 0.8$ nm, meanwhile the total thickness of the layer affected by the plasma (contaminated with Fe) was $12 \pm 1$ nm.

Fig. 9 – AES depth profile of a W$_2$N layer bombarded with D$_2$ during 1 h at $–200$ V. After the bombardment a 30 nm W layer was deposited in situ on top to protect the bombarded area from atmosphere.

A thicker W$_2$N sample was exposed in the NANO-PSI device. In order to simulate more efficiently the conditions in a tokamak divertor a 30×30×5 mm square tungsten substrate was used. A 700 nm W$_2$N film was deposited by RMS at the center with a 25 mm diameter. The sample was exposed to an Ar plasma for 9 min at $–70$V substrate bias with an estimated fluence of $5 \cdot 10^{23}$ m$^{-2}$. A mask was used to support the sample and to cover the lower part of the sample, so a step is created for W$_2$N deposited and in W bare substrate part. To minimize the intrinsic inhomogeneity of the plasma beam the part of the W$_2$N closest to the W bare substrate part was measured. The estimated erosion was $190 \pm 40$ nm for W$_2$N and $355 \pm 40$ nm for W. Three profiles were taken for each one to improve statistics.

4. DISCUSSION

4.1. SAMPLES CHARACTERIZATION

The W$_2$N samples deposited by RMS show a good crystallinity, presenting better characteristics compared with other reported results [3–6]. This can be ascribed to the large mean crystal size obtained in this work, 94 nm, compared to the ones obtained in previous works 6.5 [3] to 15 nm [5]. Also the lattice parameter, $a = 0.427$ nm is far from the results of other works $a = 0.414–0.416$ nm [3, 6], still being close to that reported for layers with an improved crystal size $a = 0.426$ nm [6]. However, the reference lattice parameter of $\beta$-W$_2$N is $0.4127$, meaning that in the films with larger crystal size the lattice is more expanded. On
the other hand, the samples obtained by exposure of pure W layers to N2 plasma (SDN method) present different characteristics. For example, a large undesired contamination from residual gases is found if very thin W layers, 3 nm, to be nitrided by plasma are used. But an undesirable multilayer structure appears otherwise if 10 nm initial W layers are used during the SDN. But if in the SDN process RMS W2N films are nitrided instead of pure W films, better results are obtained in terms of homogeneity, N/W ratio, and contamination. The similar core level spectra for nitrogen, with an 0.4 eV difference, points to a similar bonding of both type of films, but being affected by ion bombardment or more probably implanted N2, as the 400 eV peak seems to be larger in RMS W2N than in SDN tungsten nitride (9 to 6.9%), cf. Figs. 4 and 6. On the other hand, tungsten core level spectra are very different for the two studied films. RMS films present similar binding energies to previous works, while SDN films seem to be a mix between metallic tungsten and both types of tungsten nitrides: WN and W2N. In fact, by depth profile AES the 10 nm W SDN film after bombardment resulted in a multilayer of WN and W (Fig. 7). As the estimated XPS depth resolution is 5 nm for W, it could be detecting both films. However, due to the large contamination with Fe and O in SDN films, the interpretation of the core level spectra is not obvious, although the detected +0.4 eV shift in metallic tungsten peaks could be related to implanted N [1]. In order to be able to compare the SDN films with the RMS ones, a very low contamination is essential. For this purpose, a new chamber is being assembled with a lower leak rate, larger ion fluxes and the possibility of full chamber plasma conditioning.

For use on the first wall of a magnetic confinement reactor, tungsten nitride films could be deposited over the tungsten armor tiles to reduce the tungsten influx into the plasma as seen in ASDEX [1, 2]. During N2 seeding, used to radiatively cool the divertor plasma, the films could regenerate their nitrogen eliminated by the chemical sputtering from hydrogen isotopes. Nevertheless, inter-pulse nitriding by cold plasma treatment could be an easier alternative if N2 seeding is not done. For this task, films prepared by RMS have the advantages of a relatively fast deposition rate, being easy to achieve deposits in the range of microns, a relatively high decomposition temperature 820°C [6] compared to WN 550°C [13], and good crystallinity, which would lower the sputtering rate in a reactor due to the larger surface binding energy. A mandatory parameter would be low resistivity. For W2N it is reported to be within an acceptable range, 200–300 μΩ cm [3–5, 8] but larger than pure W, 5 μΩ cm, so this conductivity loss has to be taken into account. However, the resistivity increases usually with the N/W content up to 1000 μΩ cm independent of morphology [5, 8], which could render the use of SDN layers too dangerous. For WN it can be even 11,000 μΩ cm [4], but very low crystallinity films were obtained, so a morphology effect cannot be ruled out. In any case, the WN phase is not stable at temperatures likely to be exceeded in divertors of fusion reactors. As a conclusion, W2N reactive sputtered films seem to be better suited to work in a magnetic confinement reactor.
4.2. W\textsubscript{2}N PLASMA EROSION BY DEUTERIUM AND ARGON

As expected, preferential sputtering of nitrogen by deuterium was found in the ion penetration range (few nanometers). However, the nitrogen removal could also be due to a chemical reaction into ammonia, as it has been found during the N\textsubscript{2} seeding for radiatively cooling in the ASDEX divertor [2]. Experiments at larger deuterium fluxes like in PILOT-PSI are already ongoing to investigate if nitrogen is eliminated only in the ion penetration range or deeper. Nevertheless, the diffusion of nitrogen in tungsten is negligible until 600°C [1], so the nitrogen preferential elimination would be limited to hydrogen isotopes diffusion. On the other hand, the physical sputtering of W\textsubscript{2}N and WN [1] has been demonstrated to be lower than for pure W. In this work the erosion was 190 ± 40 nm for W\textsubscript{2}N and 355 ± 40 nm for W, so a decrease of sputtering of 53 ± 13 % is estimated. A reduction of 29% is calculated by SRIM program in [3] for 260 eV Ar\textsuperscript{+} ions. This lower sputtering yield is due to the similar surface binding energy of W-W and W-N, and the fact that argon atoms are better mass matched against W than WN [1].

The results are sufficiently close to account for the erosion estimation errors and the different bombardment energy. Unfortunately, due to the large uncertainties in the ion flux measurement in Nano PSI, the sputtering yield is difficult to estimate. Using the measured flux of 10\textsuperscript{21} Ar\textsuperscript{+}/m\textsuperscript{2}s with a W sputtering yield of 0.0159 at 70 eV calculated from [14], the erosion should be 131 nm. However, if the measured erosion is used to calculate the flux, then it results in: 2.6±0.3 10\textsuperscript{21} Ar\textsuperscript{+}/m\textsuperscript{2}s, not far from the measured value. More experiments at different bombarding energies are needed to confirm this sputtering yield decrease, together with a better erosion masking configuration to ease the profilometry measurements and reduce their errors. Also the sputtering by other atoms should be checked to test the conditions in a divertor plasma with seeding cooling, and to avoid the effect of the projectile mass. Ne could be a good candidate, but also He, as it is inherent to the fusion reactions. N\textsubscript{2} bombardment could be useful to confirm that the lower sputtering yield by N accumulation in W applies to tungsten nitrides too [1].

At present a large effort in the fusion community is being made towards the hydrogen isotopes retention of tungsten, due to the possible long term trapping of tritium, which could lead to an important safety issue. Although in this work no attempt has been made to measure the deuterium retention, the previously commented new experiments to be conducted in PILOT PSI will be used to assess this essential topic in tungsten nitrides. The first analysis presented very recently by many groups in the PFMC 2013 conference [15–18] points to an increased D retention at the surface due to a lower D\textsubscript{2} recombination rate and/or tungsten nitrides acting as a diffusion barrier for deuterium. The first possibility will cause a larger D retention in the crystalline defects in tungsten bulk, but the second one would greatly decrease that retention if the nitrogen layer is below the ion implantation range. However, those analyses were done in nitrided tungsten by
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plasma or ion implantation, different to the polycrystalline W₂N of this work. Even so, an increased blistering of nitrided tungsten films has been detected, which could greatly increase the erosion yield and the creation of dangerous dust [16, 17]. All those issues will be addressed in the future for W₂N films.

5. CONCLUSIONS

A successful deposition of two types of tungsten nitride layers has been shown. By sequential deposition of thin tungsten films and nitriding with N₂⁺ ions of a kinetic energy of approximately 200 eV, multilayered structures of WNₓ/W (ₓ=0.3–0.6), or homogeneous WN₀.₆ were deposited depending on the initial W thickness. However, a contamination problem has been identified due to the long plasma nitriding step. A new vacuum chamber has been designed to reduce this problem combined with plasma nitriding of W₂N layers instead of pure W.

On the other hand, pure, polycrystalline W₂N film has been made by reactive magnetron sputtering. These layers are able to be deposited in films thick enough to protect the tungsten armor tiles in a fusion reactor, and decreasing the tungsten influx into the core plasma. Also the sputtering yield seems to be half of such of pure W when compared to the bare W used as substrate, but more experiments are needed to confirm this point. It has been detected that W₂N films presents a nitrogen preferential sputtering by deuterium, probably enhanced by chemical reactions towards ammonia production. More experiments are scheduled to assess this erosion and the deuterium retention in PILOT-PSI as well.

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