Effect of boronization on plasma-facing graphite surfaces and its correlation with the plasma behavior in NSTX-U

F. Bedoya¹, J.P. Allain², F. Scotti³, B. LaBombard¹, R. Kaita⁴ and P.S. Krstic⁵

¹Plasma Science & Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02134
²Department of Nuclear, Plasma and Radiological Engineering, University of Illinois, Urbana, IL 61801
³Lawrence Livermore National Laboratory, Livermore, CA 94550
⁴Princeton Plasma Physics Laboratory, Princeton, NJ 08543
⁵Institute for Advanced Computational Science, Stony Brook University, Stony Brook, NY 11749

December 2018

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

This work was supported by USDOE cooperative agreement DE-SC0014264. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Submitted to Nuclear Materials and Energy
Effect of boronization on plasma-facing graphite surfaces and its correlation with the plasma behavior in NSTX-U

F. Bedoya1*, J.P. Allain2, F. Scotti3, B. LaBombard1, R. Kaita4 and P.S. Krstic5

1Plasma Science & Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02134
2Department of Nuclear, Plasma and Radiological Engineering, University of Illinois, Urbana, IL 61801
3Lawrence Livermore National Laboratory, Livermore, CA 94550
4Princeton Plasma Physics Laboratory, Princeton, NJ 08543
5Institute for Advanced Computational Science, Stony Brook University, Stony Brook, NY 11749

Abstract

Boronization is a Plasma Facing Component (PFC) conditioning technique widely used in tokamak machines. The National Spherical Torus Experiment-Upgrade (NSTX-U) applied this conditioning, using a plasma glow with a deuterated Trimethyl-boron (d-TMB) and He mixture. The use of boronization during the campaign improved the plasma performance, allowing longer plasma discharges and H-mode access. The chemical state of an ATJ graphite sample, used as a proxy for the NSTX-U PFCs, was monitored in-situ using the Materials Analysis Particle Probe (MAPP) diagnostic and X-ray Photoelectron Spectroscopy (XPS). The XPS data show a progressive rise (<5% to 23%) in the oxygen concentration of the boronized ATJ sample as the D⁺ fluence increased. Filterscopes were used to measure the light emitted by oxygen impurities in the plasma near the surface of the PFC. An increase in the registered magnitude of the OII line, normalized to the Dγ intensity, was observed as the concentration of O on the ATJ surface increased. The plasma performance was found to be strongly correlated to oxygen impurity concentrations at the plasma edge and on the PFC surface, as measured by the discharge length and access to the H-mode regime. In this work, we present a quantitative analysis of the evolution of the chemistry of the ATJ surface, and the oxygen presence in the plasma-material interface, and report relevant plasma parameters observed during the same period of time.
1. Introduction

The chemical state of the first wall and Plasma Facing Components (PFC) has proven to greatly affect the plasma performance in tokamaks [1]. Better density control, decreased plasma impurity concentrations and reduction of fuel recycling can be obtained when the walls are properly treated before operation of the machine[2]. Several methods of conditioning have been developed through the years for these purposes. Bake-out and glow discharge cleaning are regularly employed to remove volatile materials and surface impurities in vacuum vessel walls [1]. Additionally, methods such as siliconization, carbonization and boronization have been successfully used in different machines, improving the plasma behavior [3]. These approaches involve plasma vapor assisted deposition of thin coatings (few nm to μm thick) on the first wall and PFC surfaces, changing the physical or chemical properties of the plasma-facing materials. In the particular case of boronization, a plasma glow (Direct Current (DC) or Radio Frequency (RF)) of a buffer gas, e.g., He mixed with B carrier (B₂H₆, B(CH₃)₃, B₁₀H₁₄, etc.)[4] is used to apply amorphous boron layers on the first wall. This type of conditioning has been particularly successful in carbon machines, [4] although positive results have also been observed in high-Z devices[5,6]. The National Spherical Torus Experiment has completed an upgrade to NSTX-U, increasing the plasma current to 2MA, discharge duration to 5s and adding a second Neutral Beam Injection (NBI) source [7]. NSTX-U completed its first
experimental campaign in the fiscal year 2016 (FY16) [8,9]. During this campaign, boronization with deuterated-Thrimethyl boron (d-TMB, B(CD$_3$)$_3$) was used as the main conditioning procedure. Details on boronization in NSTX-U can be found in Ref [10]. In order to investigate the chemistry of the PFC and its evolution due to conditioning and exposures to plasmas, a surface diagnostic, the Materials Analysis Particle Probe (MAPP), was commissioned in NSTX-U during the upgrade [11]. MAPP can expose four different samples to the plasmas and during conditioning in the Outer Lower Divertor (OLD), and extract them to an analysis chamber for X-ray Photoelectron Spectroscopy (XPS) interrogation without breaking vacuum conditions and no exposure to atmosphere. More details on MAPP, and initial results from the diagnostic can be found in Ref [11,12].

The main goal of MAPP is to provide insights into the correlation between the chemical state of the PFC and its influence on plasma performance and vice versa. MAPP was used to measure the concentration and chemical evolution of ATJ graphite before and after a boronization and, additionally, to measure the progressive change on the surface produced by the plasma shots [11,13]. In this paper we report XPS and visible light spectroscopy measurements that shows a correlation between the oxygen content of the samples with that of the scrape-off layer plasma and the performance of the core plasma.

2. Materials and methods

2.1 The National Spherical Torus Experiment (NSTX-U)

NSTX-U is a spherical tokamak (R$_0$=0.93 m) [14] located at the Princeton Plasma Physics Laboratory (PPPL). The recent upgrade from NSTX increased the maximum toroidal field ($B_T$) to 1 T, the plasma current ($I_p$) to 2 MA and the Neutral Beam Injection (NBI) power
to 14 MW [7–9]. Additionally, the maximum pulse length was increased to 5 s. These changes should, in principle, provide a 5-10 times increase in the fusion triple product \((nT\tau)\) [7] compared with that of NSTX, with \(n\) being the plasma density, \(T\) the temperature and \(\tau\) the confinement time in the above expression. The main objective of NSTX-U is to provide the physics basis for a Spherical Tokamak-based Fusion Nuclear Science Facility (FNSF). The PFC in NSTX-U are ATJ (30 µm average particle size and 1.76 g/cm\(^3\) density) and POCO (AXF-5Q, 5 µm average particle size and 1.78 g/cm\(^3\) density) graphite tiles, and plasmas can be both single or double null diverted. Throughout the FY16 campaign, the PFC were conditioned using boronization with deuterated Trimethyl Boron (d-TMB). The boronizations were carried out using a DC plasma glow with a mixture of 95%He and 5% d-TMB; details can be found in Ref [10]. The conditioning was applied on the PFC either bi-weekly, weekly or daily, depending on the planned experiments. During the duration of the campaign, a total of 12 boronizations were performed.

2.2 In-situ PFC characterization with the MAPP probe
Figure 1. Three different view of the MAPP probe in NSTX-U: (a) top view of NSTX-U with the different bays labeled; MAPP is shown in bay K lower, (b) MAPP sample holder in the retracted position with the samples in the analysis chamber and (c) sample holder in the inserted position with the samples flush with lower divertor tiles [15].

The MAPP diagnostic is located under NSTX-U in bay K (figure 1), with the samples holder at \( r = 107.5 \text{ cm} \) and flush with the lower divertor tiles. In this paper we report XPS data collected with one ATJ graphite sample (the device can carry up to four different samples). The sample was exposed to boronizations and plasma discharges with no exposure to air. The base pressure in the MAPP chamber was under \( 1.3 \times 10^{-6} \text{ Pa} \) (\( 1 \times 10^{-7} \text{ Torr} \)) for all the XPS measurements, minimizing possible oxygen or water vapor interactions with the samples during analysis. The post-boronization data was obtained approximately 30 min after a boronization, and the post-plasma data were collected at the end of each day of plasma operations day (during a day the average number of plasma shots was between 15 and 20). Such frequency of data acquisition (at the end of each day) was found to be appropriate to correlate the state of the samples with the plasma performance, since, the changes observed on the latter generally occurred in the time scale of days. The XPS data were collected using a compact hemispherical energy analyzer and a dual micro-channel plate (MCP) sensor, yielding a theoretical energy resolution of 2.5 eV. The samples were excited using a water-cooled dual anode X-ray source (XRS). All the measurements were made using the Mg anode of the XRS, and the energy calibration was made with the \( 4f_{5/2} \) Au peak of a reference gold sample placed in the sample holder. Additionally, all the peak fittings were done using the CASAXPS software (v. 2.3); more details on the measurement and data fitting procedures can be found in Ref [11].
2.2 Surface visible light emission measurements

NSTX-U is equipped with a full PFC imaging suite, one of the main component of this system is the Edge Impurity Emission Spectroscopy System (EIES) or Filterscopes system [16]. The results reported in this work are based on the collection of the OII (441 nm) emission line. The signal was monitored during each plasma discharge and the trend of its intensity was analyzed as a function of time, i.e., on a shot-to-shot basis.

3. Results

3.1 Surface Chemistry

In Ref [13] we reported results on the evolution of the chemistry of ATJ graphite boronized in NSTX-U and exposed to D⁺ plasmas. There, we showed evidence of oxidation induced on the boronized graphite surfaces by the exposure to deuterium ions. A similar behavior can be seen in figure 2, this figure shows the XPS data collected during five different days with the MAPP probe in NSTX-U. The data labeled -1 were taken previous to the eighth boronization in NSTX-U; the last boron conditioning previous to that had been performed five days before. The data show a prominent oxygen peak, attributed to C-O (532.7 eV) and B-O (531.5 eV) bonds in the O1s region (left panel). Additionally, the XPS envelope shown in the B1s region (right panel) is shifted towards the high binding energy side, where the oxides are located (B₂O₃) (193.2 eV) [13,17,18].

These observations are congruent with data previously reported on boronized graphite exposed to D⁺ plasmas [13]. Following the boronization (0), the height of the oxygen envelope in the O1s region decreases considerably. The presence of B-C (187.2 eV) bonds in the C1s region (center panel) increases, and the data envelope in the B1s region is shifted
towards the low binding energy side, where the elemental boron state is located, as well as the B-C bond peak. The XPS data that follows (labeled 2 and 3), were obtained interrogating the samples after plasma exposures at the end of each day. Finally, the data labeled 5 were collected after an additional boronization and one day of plasma exposures.

![XPS spectra](image)

**Figure 2.** XPS spectra collected by MAPP during five different days with the ATJ sample in NSTX-U. Each panel shows a different photoelectron region as indicated by the top labels, i.e., O1s, C1s and B1s. The plot shows the data pre-boronization (-1), post-boronization (0), two, three and five days after plasma exposure (2, 3 and 5 respectively).

The progressive oxidation of the samples can be seen in the changes of the traces from 2 to 3; the area of the oxygen peak increases and, at the same time, the position of the data envelope in the B1s panel shifts towards the higher energies again. In this way, the XPS data show how the surface of the boronized graphite returns to the initial pre-boronization state, dominated by the presence of oxides. The appearance of the traces labeled with 5
resembles that of those labeled with 2 i.e. post-boronization and exposed to relatively low plasma fluence (compared with 3).

3.2 Surface Atomic concentrations

A more quantitative description of the behavior described in section 3.1 can be seen in figure 3. This figure shows the atomic concentrations computed from the data displayed in figure 2 as a function of days after boronization, taken as zero the day of the conditioning as previously stated.

![Graph](image_url)

**Figure 3.** Atomic concentrations of boronized ATJ graphite obtained with XPS by MAPP. The atomic percentages are plotted as a function of days after the eighth (TMB8) boronization. The plasma discharges of each day are represented by the vertical lines; labeled by representative shot numbers for each run day.
The boronizations are also shown in the figure and labeled as TMB8 and TMB9 for the eighth and ninth conditioning, respectively [15].

Figure 3 shows the measurements collected during five plasma operations days; for reference and to facilitate the analysis of the plasma performance in an upcoming section, some plasma shots are represented as vertical bars in this figure. The most representative shot of each day is marked with a thicker bar and its number is given at the top of the figure. Additionally, the boronizations are shown as grey vertical bars marked with TMB8 and TMB9 for the eighth and ninth boronizations, respectively. The XPS data were collected at the end of each day and shortly after each boronization procedure.

A high concentration of oxygen (~18%) can be observed in the sample pre-boronization (-1). A drastic change in the concentrations is registered following the boronization on day 0, the oxygen is reduced below 5% and, additionally, the highest boron concentration was measured on the same day, close to 34%; these values are typical after boronizations in NSTX-U [13]. Following two days, one of them with multiple plasma discharges (2), the concentrations were different from those measured on day 0. The concentration of oxygen on day 2 was almost double of that on 0 (8.1%) and the boron concentration decreased more than 10%. Further plasma exposures in day 3 increased the oxygen concentration but did not have an important effect on the boron concentration. It can be seen in figure 2 that the concentrations of C, O and B on day 3 were almost equal to those obtained in day -1, implying that the boron coatings applied on day 0 were saturated by the oxidation induced by the D+ irradiation. Finally, the concentrations obtained in day 5, show lower oxygen content than that measured in day 3, but higher than that expected after a fresh boronization, showing again the effect of D irradiations on the samples, as a consequence the
concentrations on day 5 are almost equal to those measured on day 2 belonging to boronized surfaces exposed to relatively low plasma fluence.

3.3 Spectroscopic measurements

NSTX-U is equipped with a full PFC imaging suite; one of the main component of this system is the Edge Impurity Emission Spectroscopy System (EIES) or Filterscopes system [16]. The results reported in this work are based on the collection of the OII (441 nm) emission line. The signal was monitored during each plasma discharge and the trend of its intensity was analyzed as a function of time, i.e., on a shot-to-shot basis.

![Figure 4](image.png)

**Figure 4** Integrated intensity of the OII line normalized by the D$_{\alpha}$ intensity (left axis in circles), loop voltage (right axis in squares) and near core electron temperature (T$_{e}$) (right axis in diamonds) plotted as a function the plasma discharge number. Three plasma shots are shown by the vertical lines (203935, 203971 and 203991).
and are the same as those in figure 2. A boronization is marked as a dashed vertical line (TMB8) as well. This metric was used in NSTX-U to assess the relative oxygen content in the plasma-surface interface [9]. As shown in figure 4, prior to the boronization, the OII/D shows a relatively high value, implying high oxygen concentrations, in agreement with MAPP’s data. In the same way, following the boronization (TMB8) the value of the ratio drops abruptly, again, a trend similar to that followed by the XPS data in figure 3. Finally, figure 4 shows how as the time and accumulated plasma fluence increase shot by shot, the value of the OII emission increase again almost linearly.

![Figure 5](image)

**Figure 5** Ejection yield of oxygen by deuterium impact of BCO:D and BCO surface. Total oxygen yield per D impact sputtered of the BCO surface with D accumulated is more than order of magnitude bigger than oxygen sputtered of “virgin” BCO surface. Data reproduced from Ref. [19] with authorization from the authors.

It is important to stress that the increase of the OII/D signal is a consequence of the increase of the chemical sputtering of oxygen with the increase of both the oxygen
concentration and the D content in the boronized carbon surface, as calculated by molecular dynamics and shown in Fig. 5. Namely, in parallel with the increase of the oxygen and deuterium concentrations on the boronized graphite surface, molecules of D and O (similar to D$_2$O molecules) as well as OD radicals are increasingly created in the top layers of the surface and sputtered to the plasma. At lowest D energies (≤10 eV) water dominates the oxygen sputtering, while at energies greater than 20 eV atomic oxygen is predominantly sputtered. In absence of accumulated D in the surface, the (atomic) oxygen sputtering of the BCO surface is about an order of magnitude smaller than that of the deuterium saturated BCO:D surface. While initial atomic concentrations of C, B and O were in ratio 60:20:20 in the pure BCO layer in figure 5, the D reached saturation depending on its impact energy. Thus, the atomic concentration of D at saturation (defined as $N_D/(N_C+N_B+N_O+N_D)$) varied between 0.12 and 0.18 for energies in range 5 to 30 eV, i.e. 0.12 at 5 eV, 0.16 at 10 eV, 0.17 at 20 eV and 0.18 at 30 eV. Since the implemented depth is a function of the impact energy (E), the D concentration at saturation was different at the various energy values. These results were extracted from molecular dynamics calculations of Ref. [19], there, the authors carefully prepared different surface targets for each D impact energy. The flux of D used to achieve saturation of the surface samples was $8 \times 10^{27}$ D/m$^2$/s (one D atom incident on a 1.7x1.7 nm surface every 50 ps). Each surface (created for each value of energy), was thermalized at 300 K and exposed to 15000 independent D impacts at normal incidence with randomly selected impact positions to obtain proper statistics of the process. More details on these molecular dynamics results can be found in Ref [19].

3.4 Plasma parameters
Figures 6a and 6b show respectively selected plasma parameters and EFIT reconstructions of discharges that occurred during days -1, 2 and 3; as marked in figures 2 and 3. The shots are also marked in figure 4. Briefly, the Equilibrium Fitting (EFIT) is a computer code that provides the solution to the Grad-Shafranov equation using as input parameters measurements of plasma parameters from multiple diagnostics e.g. external magnetic probes, poloidal flux loops and motional Stark effect probes. The code’s output includes the plasma geometry, stored energy and plasma current profiles [20,21].

It is worth mentioning that the data presented in this work were collected during the scenario development and commissioning of NSTX-U [9]. As a consequence, in many instances during the campaign, the behavior of the plasma was a function of multiple correlated variables, e.g., NBI power injected, $\beta_n$, $l$ [9], that made the task of drawing a quantitative relationship between plasma parameters and the state of the walls very difficult. However, it was clear throughout the development of the campaign that the state of the boronized surfaces and its day-to-day and shot-to-shot evolution affected the plasma, e.g., reliable H-mode access [9], plasma purity and pulse length.

The parameters shown in figure 6a belong to the same discharges corresponding to the vertical bars in figures 3 and 4. By examining these figures simultaneously, the effect of PFC conditioning on plasma performance can be qualitatively elucidated. Figure 6b shows EFIT reconstructions of the three plasma discharges at 0.250 s. As can be seen, the shapes are fairly alike, illustrating that the discharges were performed with similar settings i.e. similar shape programming within the framework of the same experiment. In the same way, the NBI power in figure 4a, shows an almost equal level of power injected in the plasma for the three discharges. As a consequence, one of the main differences between
these three plasma shots is the condition of the wall at the moment of each discharge. In this way, figure 6 compares a pre-boronization (203935), a post-boronization (203971) and a post-boronization/post-exposure discharge (203991). Shot 203935 was taken before the eighth boronization, and around five days after the seventh conditioning.

Figure 6. Plasma parameters and plasma shape reconstruction for three different discharges; pre and post boronization and post-plasma exposure. (a) Plasma current ($I_p$), Neutral Beam power Injected (NBI), line integrated electron density ($n_e$), loop voltage ($V_{loop}$) and near core electron temperature ($T_e$) (b) EFIT reconstruction of the plasma discharges shown at the same time (0.25 s) [15].

As figure 6a shows, the performance of this discharge was relatively low; the discharge does not achieve a flattop, the loop voltage (which can be used as a proxy of $Z_{eff}$ of the plasma and hence the plasma purity) during the ramp up is higher than the post-boronization discharge and its duration is around 0.3 s. As a consequence, the plasma
current reaches only around 600 kA with an 800 kA request. In this case, the maximum $n_e$ is the lowest at $\sim 2.0 \times 10^{19} \text{ m}^{-3}$ as it is the near core temperature near the plasma center (figure 4).

In contrast, shot 203971, which was performed one day after a fresh boronization, shows the benefits of the conditioning. In this case the pulse duration almost doubles reaching 0.52 s (figure 6a) with the plasma current around 800 kA at the flattop, and the lowest loop voltage during the ramp up. For this shot, the line integrated density obtained is approximately three times that of 203935, reaching around $6.0 \times 10^{20} \text{ m}^{-3}$ and the electron temperature almost doubles. These variations coincide with the high (pre-boronization) and low (post-boronization) oxygen concentrations observed with MAPP, and the high and low values in the OII/D$_\gamma$ ratio observed with the NSTX-U filterscopes. Finally, shot 203991 was taken three days after boronization and following two days of plasma exposures.

The performance in this discharge clearly decreased compared with 203971. The shot does not reach a current flattop, the plasma current approaches 800 kA briefly and the density reduces to close to 50% of the value reached by 203971. In addition, the loop voltage increases and the electron temperature drops to the pre-boronization values (figure 4). The performance of the pre-boronization and exposed post-boronization shots are similar (figure 4) as the oxygen concentrations on the plasma facing components (figure 3).

**Conclusions**

The plasma discharges shown in figures 2,3,4 and 6 were dedicated to the development of a reliable H-mode scenario in NSTX-U. The performance of the plasma during this
commissioning period showed significant variability. This work indicates that, at least in part, this variability can be attributed to the concentration of oxygen in plasma/surface interface and plasma-facing material surfaces.

Fresh boronizations produced surfaces with low concentrations of oxygen (~5%) and relatively high boron concentration, i.e., 30%. This wall composition is strongly correlated with improved operation of the machine, H-mode access and longer and cleaner discharges. Figure 6 shows an example of three discharges taken with different wall conditions; the longest discharge with the highest density and core temperature is that taken shortly after a boronization. In the same way, the parameters shown in figure 4, can be used to judge the relative amount of impurities in the scrape-off layer plasma (OII/Dγ) and in the core plasma using V_loop as an indication of Z_eff. Lower values in both parameters were achieved after the conditioning. Accordingly, figure 4 shows an increase in V_loop as the plasma fluence increases. Figures 3 and 4 show the effect of plasma exposures on the wall as a progressive increase in the oxygen concentrations in the PFC and at its interface with the plasma. Figure 5 shows that a significant increase of the oxygen sputtering with increase of the D accumulation in the surface also has to be considered when observe the increase of the OII spectrum intensity, as shown in figure 4. Battaglia et al. reported successful shape control of the plasma evolution when the changes in wall condition (and variations in the beam power) occurred in the time scale of days [9]. Such conclusions agree with our observations and further confirm the role of oxygen and related impurities in plasma performance in NSTX-U. The increments in oxygen concentration observed after ion (D2+ or He+) irradiations of boronized surfaces, have been observed in laboratory experiments, and irradiation-driven oxygen adsorption has been proposed as a possible explanation [22].
Although a more detailed study of the relationship between plasma performance and the state of the PFC is still needed, this work shows the critical role that oxygen on the tokamak walls has on the performance of the machine. We used a combination of innovative (in-situ probes) and traditional methods (visible light spectroscopy and several plasma diagnostics, as well as molecular dynamics) to analyze the evolution of the walls on short time scales (shot-to-shot and day-to-day), obtaining quantitative and qualitative information that can be used for optimized operation of the machine and to further increase our physics understanding on the plasma-surface interface. These results demonstrate the great potential of these methodologies as tools to provide answers to both engineering (machine operations and conditioning) and scientific (fundamental material science) questions.

Acknowledgements

The authors would like to thank the whole NSTX-U team for their technical and scientific support. This work was supported by USDOE BES/FES Grant No. DE-SC0010717, USDOE Contracts DE-AC02-09CH11466 and DE-AC52-07NA27344 and USDOE cooperative agreement DE-SC0014264. The digital data for this paper can be found in: http://arks.princeton.edu/ark:/88435/dsp011v53k0334.

References


Figure captions

**Figure 1.** Three different view of the MAPP probe in NSTX-U: (a) top view of NSTX-U with the different bays labeled; MAPP is shown in bay K lower, (b) MAPP sample holder in the retracted position with the samples in the analysis chamber and (c) sample holder in the inserted position with the samples flush with lower divertor tiles.

**Figure 2.** XPS spectra collected by MAPP during five different days with the ATJ sample in NSTX-U. Each panel shows a different photoelectron region as indicated by the top labels, i.e., O1s, C1s and B1s. The plot shows the data pre-boronization (-1), post-boronization (0), two, three and five days after plasma exposure (2, 3 and 5 respectively).

**Figure 3.** Atomic concentrations of boronized ATJ graphite obtained with XPS by MAPP. The atomic percentages are plotted as a function of days after the eighth (TMB8) boronization. The plasma discharges of each day are represented by the vertical lines; labeled by representative shot numbers for each run day. The boronizations are also shown in the figure and labeled as TMB8 and TMB9 for the eighth and ninth conditioning, respectively.

**Figure 4** Integrated intensity of the OII line normalized by the D$_i$ intensity (left axis in circles), loop voltage (right axis in squares) and near core electron temperature (T$_e$) (right axis in diamonds) plotted as a function the plasma discharge number. Three plasma shots are shown by the vertical lines (203935, 203971 and...
203991) and are the same as those in figure 2. A boronization is marked as a dashed vertical line (TMB8) as well.

**Figure 5** Chemical Sputtering of oxygen by deuterium impact of BCO:D and BCO surface. Total oxygen yield per D impact sputtered of the BCO surface with D accumulated is more than order of magnitude bigger than oxygen sputtered of “virgin” BCI surface. Data reproduced from Ref. [19] with authorization from the authors.

**Figure 6.** Plasma parameters and plasma shape reconstruction for three different discharges; pre and post boronization and post-plasma exposure. (a) Plasma current ($I_P$), Neutral Beam power Injected (NBI), line integrated electron density ($n_e$), loop voltage ($V_{loop}$) and electron temperature ($T_e$) (b) EFIT reconstruction of the plasma discharges shown at the same time (0.25 s).

**Figures**