WEST wall conditioning with boron: lessons for ITER and fusion power plants

E. Geulin[1], A. Gallo[1], M. Diez[1], P. Manas[1], T. Wauters[2], J. Gaspar[3], E. Hodille[1], P. Puglia[1], N. Rivals[1], T. Alarcon[1], R. Bisson[4], E. Caprin[1], G. Ciraolo[1], G. Ciraolo[1], Y. Corre[1], C. Desgranges[1], N. Fedorczak[1], G. Gervasini[5], A. Grosjean[6], C. Guillemaut[1], B. Guillermin[1], J. Gunn[1], A. Hakola[7], J. Hobirk[8], K. Krieger[8], L. Laguardia[5], R. Lunsford[9], P. Maget[1], R. Mitteau[1], Ph. Moreau[1], R. Pitts[2], D. Sgrelli[1], E. Tsitrone[1], N. Varadara[1], S. Vartanian[1], A. Widdowson[10], the WEST team*, and EUROfusion WPTE team**

[1]CEA, IRFM, Saint-Paul-les-Durance Cedex, France
[2]ITER Organization, 13067, Saint-Paul-Lez-Durance, France
[3]Aix-Marseille University, CNRS, IUSTI, Marseille, France
[4]Aix-Marseille University, CNRS, PIIM, F-13397, Marseille, France
[5]Istituto per la Scienza e Tecnologia dei Plasmi–CNR, Milano, Italy
[6]Department of Nuclear Engineering, University of Tennessee USA
[7]VTT, PO Box 1000, 02044 VTT, Finland
[8]Max–Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748, Garching, Germany
[9]PPPL, Princeton, NJ 08543, USA
[10]UKAEA, Culham Campus, Abingdon, OX14 3DB, UK
*West team
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Boronization plays a crucial role in fusion devices with full tungsten first wall like ITER. Wall conditioning is essential to improve plasma performance, and ensure efficient operation. Glow Discharge Boronization (GDB) is widely used to reduce the effect of impurities in tungsten environment and to facilitate plasma breakdown, burnthrough, current ramp-up, and to access high-performance discharges [1]. WEST, a tokamak with long pulse capabilities ([2]) and actively cooled tungsten plasma-facing components, provides a unique platform to study the effects of GDB under reactor-relevant conditions [3]. This contribution reviews key aspects of boronization and its impact on the operation of full tungsten machines like WEST and ITER.
In particular the following open questions are addressed. In terms of impurity reduction it is important to characterize how efficient GDB is for lowering oxygen and tungsten contamination (O/W) in the plasma, to improve overall plasma cleanliness. Understanding how boron layers impact fuel retention is poorly characterized but is crucial for fuel management in future power-plant. As ITER is considering a toroidally non-uniform GDB set-up, it is important to assess whether non-uniform conditioning can achieve comparable results to those from uniform GDB. After a vent, for ITER it is important to establish whether an efficient and reliable start-up can be achieved in a full tungsten environment without GDB. The Impurity Powder Dropper (IPD) is a potential method to improve plasma conditions by injecting boron directly into a plasma discharge. After a successful restart, it would be of interest to assess if it may delay the need for full GDB during a campaign.

In order to study the boronization lifetime and impact on fuel retention, identical plasma discharges were conducted before and after a standard uniform WEST GDB, injecting 10g of B (from a He + B_2D_6 mix as foreseen for ITER). The scenario included 60 seconds of L-mode with 3.7 MW of Lower Hybrid Current Drive (LHCD). Following the GDB, four 14-second ohmic discharges preceded the return to the 3.7 MW LHCD scenario. Key observations are:

- Radiation losses decreased by 15% after boronization, gradually fading over ≈ 300s of plasma. After the wall conditioning sequence the signal intensity of H_2O is reduced by a factor of 10 and the O_2 signal by a factor of 3, as measured by the mass spectrometer. [3].
- After the GDB, particle balance indicates an increased retention of the fuel by the boronized wall for the 4 to 5 first pulses. Fuel retention then goes back to similar level as before the GDB after those 4 to 5 pulses, indicating a short lasting impact (< 100 s of plasma in WEST conditions). GDB is also seen to impact the distribution between mass 2 (mainly H_2), 3 (mainly HD), and 4 (accounting both He and D_2) in the exhaust gas, as shown in the RGA measurement of Figure 1.

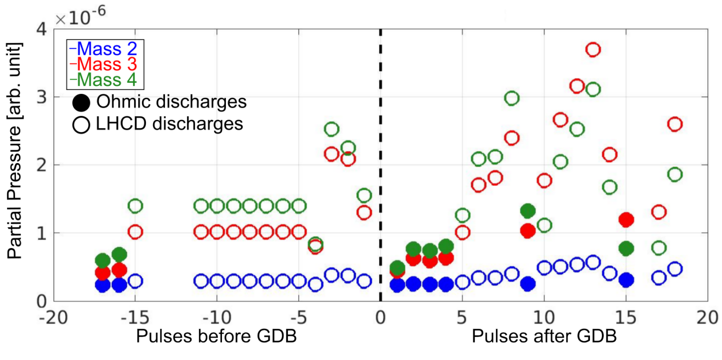

Figure 1: Partial pressure as derived from RGA measurements in the divertor exhaust gas before and after the GDB (vertical dashed line) for 3 different masses.

The effects of non-uniform boronization were studied in WEST at the begining of the fall 2024 campaign, when the machine was equipped with new W bulk bumper tiles. This campaign started without GDB, and after two days, was followed by one GDB using only half of the injection points (Figure 2). The figure also shows the positions of two boronization collector probes being deployed for direct measurements of the boron layer thickness and the uniformity of the boron deposition. The boron deposition is predicted by Monte Carlo tracing of diborane in a simulated glow discharge plasma background, following the approach that supported the design of the boronization system of ITER [4]. Results from modelling were used to optimized the non-uniform set-up of GDB for WEST, so that one of the collector probe is located in an area of less predicted boron deposition. Tungsten and stainless steel samples were exposed to both uniform and non-uniform GDB. After visual inspection samples exhibit distinct features in terms of deposition. At the time of writing the post exposure analysis is ongoing.

Plasma operation without GDB was initially challenging. Before the GDB, none of the requested ohmic discharges were achieved due to radiative collapse. In contrast, immediately after the non-uniform GDB, most requested discharges were successful as summarized in Figure 3. These results were in line with what was observed in ASDEX Upgrade [5]. Despite this non-uniform GDB, the machine operated for two months without any further GDB, achieving a total of 7614 seconds of plasma (including a record plasma duration at the time [2]) representing 12.5 GJ of injected energy.

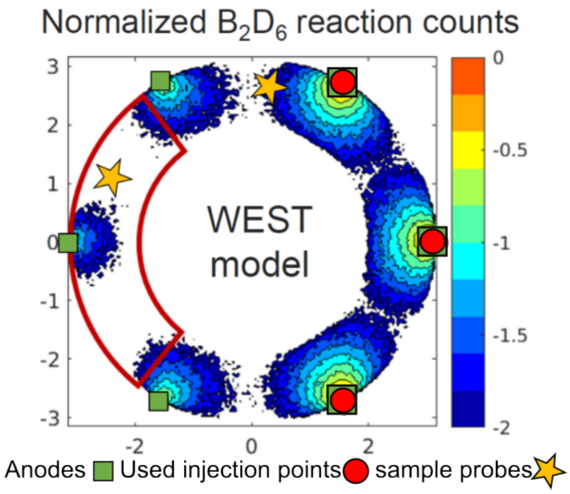

Figure 2: Top view of WEST showing toroidal position of glow anodes and diborane injection points usable during boronization. Colormap showing the diborane reaction rate from Monte Carlo tracing [4] of diborane in a glow discharge plasma background of WEST.

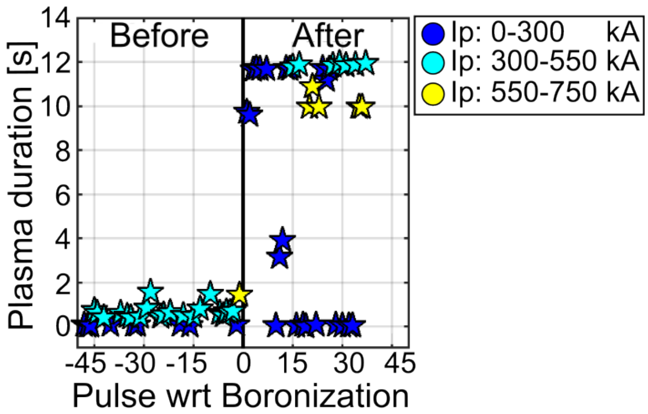

Figure 3: Plasma duration and current before and after GDB with bulk tungsten tiles and half of the injection points used.

WEST also has the capability to study the effects of real-time wall conditioning via on-demand Boron injection into plasma pulses utilizing an Impurity Powder Dropper (IPD) [6, 7]. The IPD proved to be a promising complement to GDB as it can be used to reset adverse plasma conditions by dropping B powder in ohmic or LHCD-heated L-mode plasma discharges, enabling scenarios that were otherwise unattainable on a given day. Ongoing studies aim at quantifying the minimum B mass to be dropped to achieve long plasma discharges without GDB and at studying the degradation of the IPD-B conditioning effect in particular in case of disruptions. Finally, results from WEST are compared to complementary GDB experiments carried out in ASDEX Upgrade.

Experiment on GDB were carried out in both ASDEX Upgrade and WEST, and the outcome will be compared in view of lessons learn for ITER.

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