New boronization system at ASDEX Upgrade

M. Dibon[a], V. Rohde[a], F. Stelzer[a], K. Hegele[a], M. Uhlmann[a], ASDEX Upgrade Team

[a]*Max-Planck-Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany*

The coating of plasma facing components (PFC) with boron significantly improves the performance of plasma operation in magnetic fusion devices. The boron layer traps residual oxygen in the vacuum vessel, thus reducing radiative losses due to collisions between the plasma and this impurity. Furthermore, it reduces the erosion of high-Z material from the plasma facing components due to plasma wall interaction. This prevents accumulation of high-Z impurities in the plasma during discharges. The coating is achieved by deposition during a glow discharge using diborane (B_2D_6). A new system for injecting diborane into the vessel, pumping and treatment of residual process gas was installed at ASDEX Upgrade. This new system allows semi-automatic boronization cycles with adjustable process times and pressures, resulting in different boron layer thicknesses. A feedback loop between mass flow controllers in the gas supply and a pressure gauge at the vacuum vessel keeps the process pressure constant at the optimal value to create a homogeneous boron layer. The system meets industrial safety standards for the treatment of the toxic diborane gas.

Keywords: wall conditioning, plasma wall interaction, boronization

I. INTRODUCTION

Wall coating with boron is a common practice at all medium and large magnetic fusion devices like DIII-D[1], Tore Supra[2], KSTAR[3] and W7-X[4]. Whereas boronization was invented to improve the plasma performance by gettering residual oxygen in the vacuum vessel, covering of high-Z plasma facing components dominates for nowadays metal devices[5, 6]. Due to the size of ASDEX Upgrade (AUG), ITER relevant core scenarios are only possible with a hot low radiation SOL plasma, which results in a significant W influx to the core plasma. Consequently, the performance of these scenarios is limited. To solve this problem the PFCs and specially the ICRH limiters are regularly coated using a boronization and the sensitive experiments are clustered to the days after this. Additionally wall coating is applied in AUG after a vessel vent, to reduce the oxygen content resulting from water released by the carbon tiles.

At AUG, a glow discharge in He and diborane is used to decompose the diborane, which is deposited at the PFCs forming α-BH layers[7]. The use of diborane offers the possibility to use deuterated species, which are needed as hydrogen reduces the plasma performance. Unfortunately, diborane is highly toxic and flammable which requires a dedicated procedure including restrictions to access the building. During the operation phase, a fresh boronization is applied after typical 180 plasma discharges or 1500 s of operation.

Currently, an alternative by dropping boron powder into a highly heated plasma discharge is investigated at AUG. The boron is recycled in the scrape-off layer and deposited on the PFCs[8], especially at regions with plasma contact, which will dominate the W influx in recent discharges.

The boronization system at AUG, build in 1988, required evacuating the building and could only be operated in the late evenings. The demand for more frequent boronizations with thinner layers, as well as new safety regulations for flammable gases called for a new boronization system. Therefore, the AUG boronization system was completely rebuilt in 2019. This included a new gas cabinet for gas supply, new gas lines from the gas cabinet to the torus and a new pumping system for the residual process gas from the vacuum vessel. This report contains the setup of the gas supply, the glow discharge system in the torus, as well as the arrangement of the pumping system. Furthermore, the boronization process is explained and technical performance of the system is shown.

II. BORONIZATION SYSTEM

The boronization system can be divided into three main parts. The first one is the gas supply with the gas cabinet, the pumping for process gases, exhaust with monitoring and the gas lines to the torus (BOR control). The second one is the glow discharge system in the torus with the glow anodes (GES control) and the third one is the torus pumping system (TPS control) consisting of different pumping stages, gas treatment and monitoring. All systems are controlled with own networked PLC controls type Siemens SIMATIC S7-300/S7-400. The complete boronization system is shown in Fig. 1.

The gas cabinet contains the gas bottles for the diborane gas mixture (10 % B_2D_6 + 90 % He, 7.8 l, 7 MPa) and for the helium (50 l, 20 MPa), which is used for testing, wall cleaning and flushing of the gas pipes. All connections in the cabinet are welded or metal sealed to prove long-term tightness. The diborane gas bottle is directly connected by an all-metal seal to a three-way pneumatic valve block with short connection length to keep the trapped gas amount as low as possible. After installation, the tightness of the diborane connections are tested by 1.6 MPa He via the regulator REG_2R before the bottle is opened manually. The connection of the bottle can be cleaned by puff and purge into an absorber installed in the cabinet driven using a venturi pump operated with nitrogen at 0.6 MPa, which dilutes the optional used D_2 gas below the explosive concentration. It was calculated, that the absorber could be used for 30 evacuations of the diborane in the system before it is saturated. The regulator REG_L adjust the diborane process pressure to 0.15 MPa as needed for the MFCs. This low-pressure part of the rack can be cleaned by He flushing and evacuation by the 3 port valve LPV_L again into the absorber by the venturi pump. The gas inlet to the torus is controlled by two flow controllers (MFC) as two inlet ports are installed for homogeneous coatings.

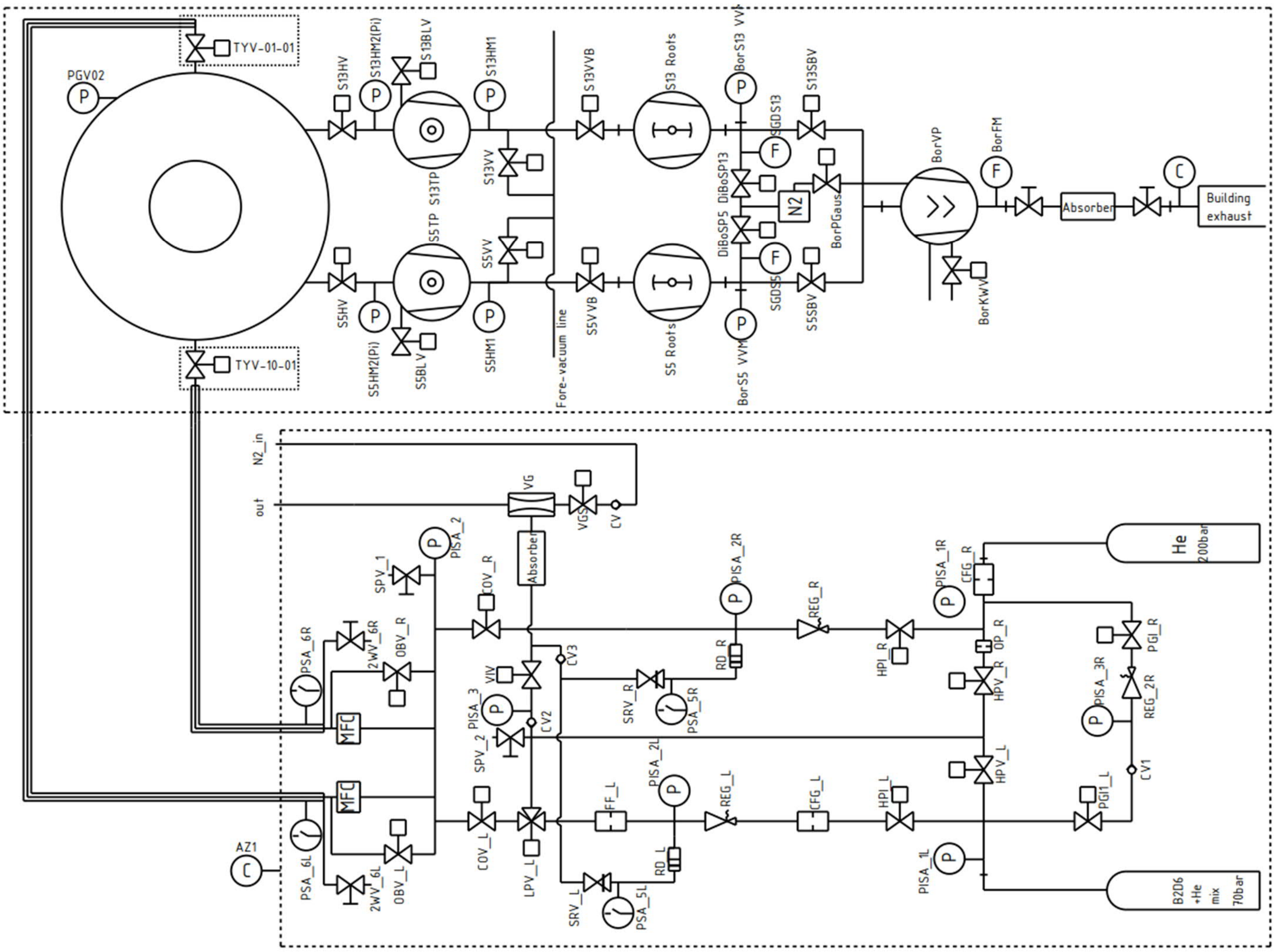

Figure 1: Schematic of boronization system on ASDEX Upgrade. Explanations of the names and symbols can be found in section II

Additionally, a helium supply with a separate cylinder is installed in the cabinet. Beside leak tests and flushing for cleaning purpose, the He can also feed the MFCs. This is needed for function tests of the whole system, which are done as part of the boronization procedure. Most of the components in the rack are designed to operate at pressure up to 0.8 MPa. To protect them in case of a malfunctioning regulator, both gas lines are equipped with rupture discs (RD_L, RD_R), which open at 0.5 MPa, pressure switches (PSA_5L, PSA_5R) and relief valves (SRV_L, SRV_R), which open at 0.6 MPa.

The gases pass through both MFCs, which are used to regulate the gas pressure in the torus. They allow a flow of 2 Pam^3/s in total while requiring an inlet pressure above 0.1 MPa. If the supply pressure drops below that pressure threshold due to empty bottles, the MFCs can be bypassed through OBV_L and OBV_R to deplete the gas in the bottles completely. After the gas has passed through the MFCs or the bypass valves, it enters the two gas lines to the torus, which are each about 20 m long and run through the torus hall. These gas lines are built as 1” coaxial pipes. The outer pipes are evacuated and monitored by pressure switches PSA_6L and PSA_6R. If the pipes are damaged, the vacuum is broken and the pressure switches shut down the process. The inlet valves into the torus TYV-01-01 and TYV-10-1 are located on opposite sides of the torus to have a more uniform gas distribution in the torus. The flame resistant gas cabinet, which is located outside the torus hall, is constantly vented into an exhaust, which leads outside the building. The gas from the venture nozzle is blown into the same exhaust, which is equipped with a diborane monitor.

The glow discharge system was adopted from the old boronization system[9]. It consists of four glow anodes, which are installed symmetrically around the torus magnetic low field side. Typically they are operated with 2 A and 540 V each. The old system achieved uniform boron layers, as observed by visual inspection after a vessel vent[10]. Hence, it was decided to reuse the glow discharge system for the new boronization system. The pumping system was redesigned to allow operation of the glow discharge with either D_2 or He in the diborane gas mixture. To gain a safer operation the previously used thermal decomposers were replaced by an industry filter system. Two turbomolecular pumps (S5TP, S13TP), which are part of the regular torus pumping system, located 90° from the gas inlet, are used. The turbomolecular pumps are Pfeiffer TPU2301P, which are usually connected to the fore-vacuum line via the valves S5VV and S13VV. During boronization, these valves are closed and the exhaust gas is routed through valves S5VVB and S13VVB to the new diborane pumping system. A dry screw pump (Leybold DRYVAC DV650 ATEX) which is vacuum tight and allows hydrogen operation, was selected as roughing pump. Presently no roughing pumps, which are certificated for diborane operation, are available. Hence, the input gas has to be inertised before it reached the roughing pump. For this reason nitrogen with a flow of 4000 l/s, resulting in a pressure of 300 Pa, is needed. This dilutes the diborane gas below the explosive concentration of 0.9% and can safely enter the screw pump. As this results in a pressure to high for the operation of the turbomolecular pumps, two roots pumps (S5 Roots, S13 Roots) were added to the system. These pumps are of the type Leybold RUVAC WSU251 and they create the necessary fore-vacuum pressure below 110 Pa for the turbomolecular pumps. The nitrogen flow is constantly monitored during boronization using the flow meters SGDS5 and SGDS13 and a drop of the N2 flow would terminate the process. The dry screw pump is installed directly beneath the torus hall chimney. The pumps and valves are connected by fully welded 76.1 x 2 mm stainless steel pipes, which run along the torus hall floor. The diborane exhaust gas is fed into a chemical absorber while the flow between pump and absorber is constantly monitored with a thermal flow meter (BorFM) to detect a blockage downstream. The absorber is a CS CLEANSORB CS025LS. Its capacity is large enough to take in the content of the entire diborane bottle at full pressure in case of a major malfunction. The gas coming out of the absorber is checked by a diborane monitor before it is vented into the chimney.

III. BORONIZATION PROCESS

Before the boronization process starts, all safety-relevant components on the TPS are checked during fully automated sequences to guarantee perfect functionality. Once this is established and the torus hall is void of all personnel, the torus gas inlet control (GES) is given the approval to start the first helium glow discharge. This first helium glow discharge is run for about three hours and is used for wall cleaning. After this wall cleaning discharge is finished, the glow discharge is terminated and the gate valves between the turbomolecular pumps and the torus are closed by the torus pumping system (TPS) except for S5HV and S13HV. After confirming that the gate valves are closed and the purge system of the TPS is activated (SGDS5 and SGDS13), the control system of the diborane gas cabinet (BOR) is enabled to initiate the boronization program. The helium line in the gas cabinet is opened and the MFCs regulate the vessel pressure to 0.5 Pa. When this pressure is within a tolerance of 0.05 Pa over 5 minutes, the glow discharge is started. This helium glow discharge is run typically for 10 minutes and it is used to establish a stable glow discharge. The closing of the helium line and the opening of the diborane line in the gas cabinet are done in parallel and the glow discharge is not interrupted to ensure that diborane gas is converted in the glow plasma. The glow discharge in the He & B_2D_6 gas mixture is continued for several hours before switching back to helium, which is also done without interrupting the glow discharge. The helium glow discharge is maintained for about 15 minutes to purge the gas lines from remaining diborane before the helium line in the gas cabinet is closed and the glow discharge is terminated. During the entire time of the boronization, all currents of the glow discharge (He & B_2D_6) are measured and analyzed every 200 ms through the GES control. A deviation of the currents by more than 50 mA from predefined values (1900 mA, see IV.) would cause the GES control to interrupt the glow discharge. When the pre-set boronization time, which includes the He wall cleaning discharges, on the BOR control has expired, the TPS is prompted to open all torus gate valves and to close the purge valves. The GES control then starts the final cleaning, which is usually run for 15 minutes. The system has been tested with process times of 5 to 10 minutes. However, good boron layers require longer wall cleaning and boron deposition times.

IV. TECHNICAL PERFORMANCE

To classify the kind of layers produced by the glow discharge, Si wafers were exposed using a manipulator system during a boronization. Ion beam techniques offer the possibility to get the material composition. It turned out that typical α-BCD layers are produced[10]. Ion beam analysis revealed the atomic density of the boron on the sample surface. This was compared to the amount of boron that was injected into the torus as diborane gas, which showed a nearly perfect decomposition efficiency. Additionally, some tiles were analyzed using XPS[11]. Most of these investigations were done before the complete transition of AUG to W plasma facing components. As the carbon concentration was strongly reduced, the effects of the boronization on the plasma behave similar. The only change was the stability of the layers on air, i.e. after a vessel vent. Now the layers are forming a white dust, as they react presumably with water. Residual gas analysis is strongly hampered during boronization, as the diborane reacts with the filament, so the operation time has to be reduced. When comparing mass spectra with and without glow discharge, it was found that 97 % of the diborane gas had been disintegrated. The new boronization system and its maintenance features (bottle changing program, purge program) were tested thoroughly with helium before switching to the diborane gas mixture for the first boronization in December 2019. The system has since undergone improvements concerning usability and safety, like the visualization of timers or the implementation of the diborane monitors into the building alarm system. The results in Fig. 2 show the system parameters during the boronization on June 5 2020, which indicate the overall system performance. It can be seen that the supply pressures for the MFCs remain constant during the different stages of the boronization process. This is important to allow the MFCs to regulate the flows precisely and not have fluctuations, which would result in a varying torus pressure. The flows overshoot slightly when gas is first let into the torus or when the gas species is changed from helium to diborane and vice versa. This overshoot is a result of the feedback loop between the MFCs and the baratron pressure gauge at the torus. The pressure gauge responds with a delay to the increasing flow through the MFCs, leading to a pressure above the desired 0.5 Pa in the vessel. The MFCs react and reduce the flow until the requested pressure is reached. Feedback oscillations are suppressed by slowly opening or closing the MFCs.

After the initial overshoot of, the flows remain constant through the single process steps. This is also reflected by the linear decreasing pressure in the diborane bottle. The overall consumption of the diborane gas mixture is 6.8 kPam³ for a three hours diborane glow discharge. This allows eight boronizations of this kind before the bottle has to be replaced. The currents in the glow plasma remain constant at 1900 mA during the entire glow discharge.

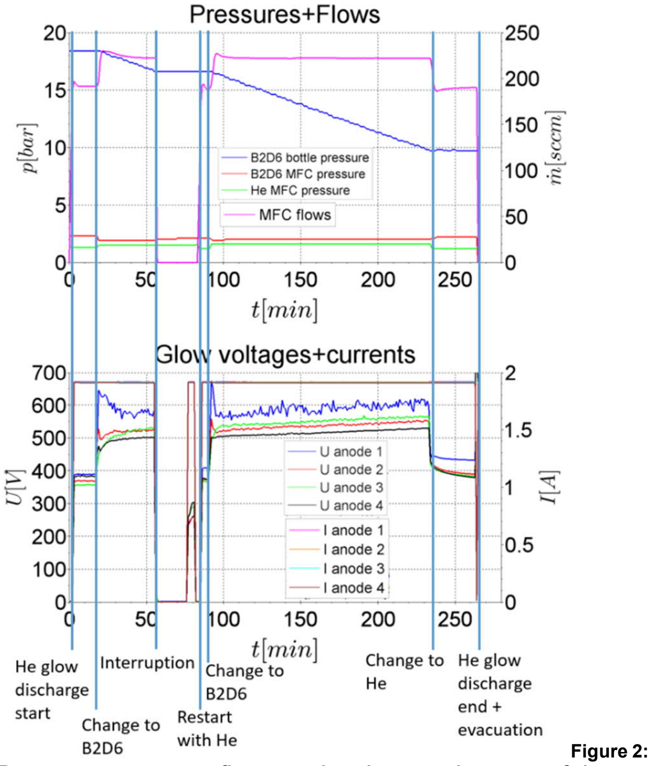

Figure 2: Process pressures, gas flows, anode voltages and currents of the new boronization system

The voltages at the glow anodes are rather constant at about 380 V during the first helium glow discharge before jumping up to about 500 V after the process gas is switched to the B_2D_6 gas mixture. The diborane gas requires a higher voltage because of the larger Ion radius of the boron. At the end of the diborane glow discharge, the voltages have reached values around 550 V. This linear increase of the glow voltages can be explained by the temperature increase of the anodes. After switching back to helium, the voltages drop back to about 400 V. Anode 1 shows much stronger voltage oscillations than the other three. This behavior affects the quality of the boron coating and is currently under investigation.

There is an interruption in the process between minute 57 and minute 87. This was caused by a short incident in the pumping system, which triggered an automated termination of the boronization process. Since the new boronization system can be operated without precautionary evacuation of the building, the tokamak systems and diagnostics are still operated and tested during boronization. This influences the auxiliary systems like compressed air or the nitrogen supply, which are necessary for the pumping system. After this cause of the problem had been identified, the boronization process could be resumed immediately. Overall, the system parameters, particularly the pressure, are constant or vary in a low margin during the entire boronization process. This leads to a homogeneous boron layer in the tokamak, like with the old system.

V. SUMMARY AND OUTLOOK

A new boronization system was installed at ASDEX Upgrade, consisting of a flame retardant gas cabinet containing the diborane and helium gas supplies, coaxial gas lines to the torus and a new pumping system for the potentially toxic and flammable exhaust gas. The glow discharge system was adopted from the old boronization system. The system is constantly monitored by diborane detectors, pressure gauges and flow meters. Implementation of these safety features into the building alarm allow boronizations without precautionary evacuation except for the torus hall. Chemical absorbers in the gas cabinet and after the pumps prevent diborane from leaving the system. The boronization process is semi-automated with minimal manual input necessary to initiate the process. The control system of the boronization system is fully integrated into the machine controls to coordinate it with the other gas, vacuum and valve control systems. The boronization systems shows constant system parameters during the boronization process, which generates a homogeneous boron coating in the tokamak.

In the near future, it will be investigated whether shorter and more frequent boronizations have a positive impact on the plasma performance. Experiments could profit from more stable wall conditions. Furthermore, boronizations could be adjusted to the experimental program. This is possible since no evacuation is necessary anymore and the semi-automated process allows easy adjustments of the process times for both helium and diborane glow discharges. The B_2D_6 + He gas mixture that is currently in use will be replaced by a B_2D_6 + D_2 gas mixture. This prevents implementation of He in the boron coating and thus reduces helium impurities in plasma experiments. This is possible because the new pumping system was designed to operate with explosive gases and uses components compatible with hydrogen and deuterium.

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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]G.L. Jackson,J. Winter, K.H. Burell, Journ. Of Nucl. Mat. Vol 196-198, p. 236-240 (1992)

[2]E. Gauthier, C. Grisolia, A. Grosman, Journ. Of Nucl. Mat. Vol 196-198, p. 637-641 (1992)

[3]Suk-Ho Hong, Kun-Su Lee, Kwang-Pyo Kim, Journ. Of Nucl. Mat. Vol 415, p. 1050-1053 (2011)

[4]S. Sereda, S. Brezinsek, E. Wang, Nucl. Fusion Vol. 60, 086007 (2020)

[5]A. Kallenbach, R. Dux, M. Mayer, Nucl. Fusion Vol. 49, 045007 (2009)

[6]B. Lipschultz, Y. Lin, E.S. Marmar, Nucl. Mat. Vol 363-365, p. 1110-1118 (2007)

[7]A. Annen, M. Saß, R. Beckmann, Thin Solid Films, Vol. 312, Is. 1-2, p. 147-155 (1998)

[8]A. Bortolon, V. Rohde, R. Maingi, Nucl. Mat. Ener. Vol. 10, p. 384-389 (2019)

[9]T. Härtl, A. Drenik, M. Kircher, Fus. Eng. And Des. Vol. 124, p. 283-286 (2017)

[10]V. Rohde, R. Dux, A. Kallenbach,Nucl. Mat. Vol 363-365, p. 1369-1374 (2007)

[11]V.Rohde, R. Neu, R. Dux, 26th EPS Conf. on Controlled Fusion and Plasma Physics (Maastricht, 14–18 June 1999) Vol 23J(ECA) p. 1513–16