Optimization of the ASDEX Upgrade glow discharge

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The ASDEX Upgrade (AUG) system for glow discharge (GD) has been revised comprehensively. This was necessary due to technical as well as operational requirements. The available space with in the low field side of the vacuum vessel is strongly limited because it's the preferred place for diagnostics. The new development based on the design of the W7-X anode now has a smaller footprint, is long term reliable and easier maintainable. Additionally each of the anodes is equipped with a separate starting device. The use of this device now allows the fast ignition of GD at operational pressure without the need of a short-term pressure increase.

With the change from carbon to tungsten plasma-facing components (PFCs) an enhanced Helium (He) content at plasma discharges was observed for unboronized walls and the implantation of He during GD could be identified as source. For this reason the use of He GD has to be strongly reduced. It turned out that pulsed GDs of about 10 seconds length followed by a pumping down phase are sufficient to clean the wall. This mode of operation requires a reliable breakdown of the GD at operating pressure. This paper gives an overview of the technical setup and first measurement results.

Keywords: ASDEX Upgrade, glow discharge cleaning, GD, GDC, wall conditioning, pulsed GDC

1. Introduction

The transition from carbon to metal PFCs changes the role of wall conditioning in present day fusion devices. Where GD conditioning (GDC) in-between almost all plasma discharges was common practice at the times of carbon walls to ease plasma start up, the application in the present metal wall devices is ambivalent [1]. For a well-conditioned wall (i.e. after a few experimental days with plasma operation), GDC is not necessary anymore for regular plasma discharges. The release of adsorbed He from tungsten wall material in the subsequent plasma discharge even lead to high He concentration and thereby a reduced performance [2]. On the other hand GD is still important for conditioning the walls after vessel vents or impurity events as for instance massive gas injection, which is needed to reduce the forces induced by plasma disruptions [3]. Furthermore it is essential for wall coating such as boronisation which is done by GD induced dissociation of gaseous Diboran.

For the use in ITER several wall conditioning techniques that can also be implemented in the presence of a magnetic field are envisaged [4], but GD techniques, whose application is reliable and simple, are still the working horse for successful plasma start up.

2. Glow discharge cleaning

The principle of GDC is the use of accelerated ions to desorb particles from the walls. In the all tungsten AUG device GDC is regularly performed for the reasons given above. These GDCs are done in He or the currently used operational gas for the plasma discharges e.g. Deuterium (D_2). However He is preferably avoided as a high He wall content interferes especially with low density discharges [5] or is at least exchanged by a subsequent D_2 GDC.

Breakdown of a GD is always an issue, especially in an unconditioned device. Within the dimensions of a midsize tokamak GD can be started with ignition voltages of about 2.5 kV at a pressure of about 5 Pa [6]. At these pressures, depending on the gas species, hollow cathode type discharges could start in ports or constricted rooms staying also after reducing the pressure due to a considerable hysteresis effect [7].

Increasing the pressure for ignition and adjusting it afterwards to the typical GD operating pressure of about $3\ldots5\cdot10^{-1}$ Pa usually takes several minutes of operational time without any cleaning efficiency. To prevent diagnostics from higher pressures also the closing of gate valves is necessary which requires additional time and certain operational efforts. Safety aspects to recognise and avoid hollow cathode discharges have to be taken into account.

Due to these reasons it is advantageous to start GD straight at the operating pressure with the help of an independent starting device.

3. Technical setup AUG GD system

3.1 GD electrodes and starting devices

One W7-X prototype electrode [8] was installed over three experimental campaigns from 2008 to 2011 in the AUG vacuum vessel. It was operated in combination with the originally installed rod-type electrodes replacing one of the four. Comparison of both GD-electrode types showed a significantly lower discharge voltage depending on pressure of more than 30% [9]. The positive operational experiences as well as mechanical advantages like a small footprint, simplified maintenance and improved reliability resulted in the decision to develop a new electrode similar to this design but non

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water-cooled and adapted to installation requirements of AUG.

The electrode consists of several components that are necessary for mechanical stability and electrical isolation. The cylindrical stainless steel housing is equipped with three boreholes evenly distributed on a bolt circle for receiving the mounting screws.

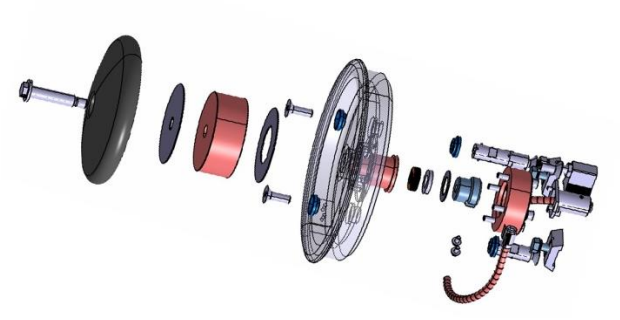

Fig. 1. AUG glow electrode, exploded assembly drawing (main components from left) TZM screw, tungsten-coated graphite anode, alumina isolation with graphite foils, stainless steel housing.

The design of the cylindrical alumina block (Al_2O_3) with a thickness of 26 mm ensures electrical isolation even if partly coated with conducting material eroded from AUG PFCs. To minimize mechanical point loads under the thermal stress caused by the temperature rise of the anode to up to 700°C a graphite foil is installed on both front sides of the ceramic.

The anode is machined from a block of fine-grain graphite, coated by PVD technique with a layer of 10…15 µm of tungsten to comply with ongoing carbon-free machine requirements. The separate components are jointed together with a central screw coupling made of TZM (Titanium-Zirconium-Molybdenum) to withstand the high heat stress. This construction allows an easy disassembling of components for cleaning or maintenance purposes without removing the housing and the electrical cabling.

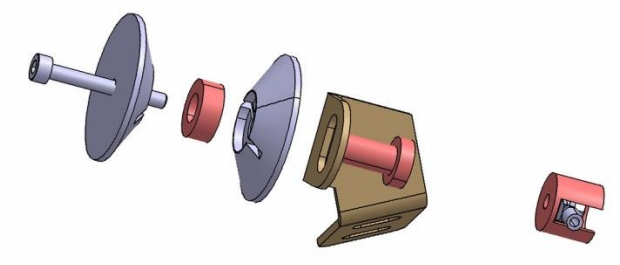

Fig. 2. Starting device, (from left) screw, cone (high voltage side), isolator graphite coated for surface discharge, cone (vessel potential side), bracket to GD-electrode, electrical connector.

In laboratory experiments within a bakeable 0.5 m^3 vessel comprehensive tests of the effectiveness of separate starting devices (SD) were undertaken. Different technical constructions as well as variation of the position of the SD related to the GD-electrode were investigated. All these tests finally confirmed that a SD enabling a surface discharge installed close to the GD-electrode provides the most reliable ignition [10].

The SD consists of two opposite facing cones isolated by a disk made from alumina. This ceramic isolator is coated with a thin film of carbon and thus enables surface discharges. The left cone is electrically isolated and linked to the screw terminal. The right cone is galvanically connected to the bracket mounting the SD to the GD-electrode housing. Thereby it is on the same electrical potential as the vacuum vessel.

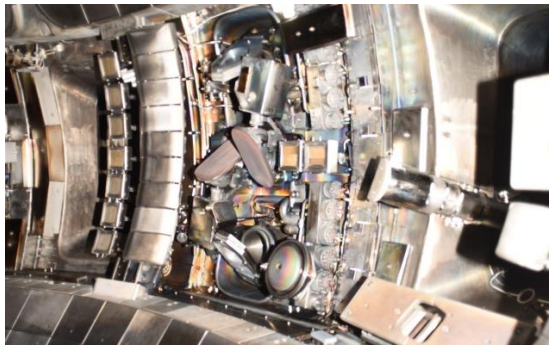

Fig. 3. GD-electrode with SD in AUG, typical mounting situation in the congested low field side.

Four GD-electrodes were installed during the planned maintenance 2013 in the region of the machines mid-plane low field side. As far as limited space conditions allowed they are evenly distributed on the circumference in the sectors 3, 8, 14 and 16. For redundancy each electrode is equipped with an individual SD.

3.2 GD gas inlet

The GD gas inlet is located in an upper port (Co02). It consists of one gate valve to separate the common system from the vacuum vessel and three mass flow controllers (MFC) with a maximum flowrate of 10,000 sccm each calibrated in He, H_2 and D_2. Every MFC has its individual shut-off valve. AUG main gas transfer vacuum pumping system is located at the lower (Cu) ports and therewith as fare as technically possible away from GD gas inlet. Gas flow of one single MFC can be regulated in a range to achieve vacuum pressure between $1 \cdot 10^{-2} \ldots \approx 2$ Pa at full AUG gas transfer pumping speed of typical 7000 l/s (all 11 turbo molecular pumps operating).

3.3 GD anode and SD power supply

The AUG GD power supplies were already renewed in the year 2002. Due to good operational experiences over many years and for cost saving reasons, a replacement of the PSs (E&A 4002K-2LCD, max. output current 2 A, max. output voltage 2 kV, max. output power 4 kW) wasn't considered, also because the maximal achievable current density of about 160 mA/m^2 appears to be perfectly sufficient [11].

Laboratory tests showed that GD reliably starts using the SD at a voltage of 2.5 kV or more. However, arc-over on the SDs already appears earlier at voltages of a few hundred volts. To minimize the associated material removal which releases small amounts of carbon and erodes the stainless steel cones of the SDs, it is beneficial to cut-off the powering of the SDs completely after successful igniting the GD. In the former technical setup each SD was powered commonly with the associated GD-anode via an electrical resistor. This setup ensures that current flow over the SD is limited in case of short-circuit and the GD anode remains operable.

This resistor was often damaged by overheating. A separate cabling permits the operation of the SD by an independent PS. This also allows overcoming the previous voltage limitation of 2 kV for the SDs, which is beneficial for breakdown the GD also with unconditioned PFCs.

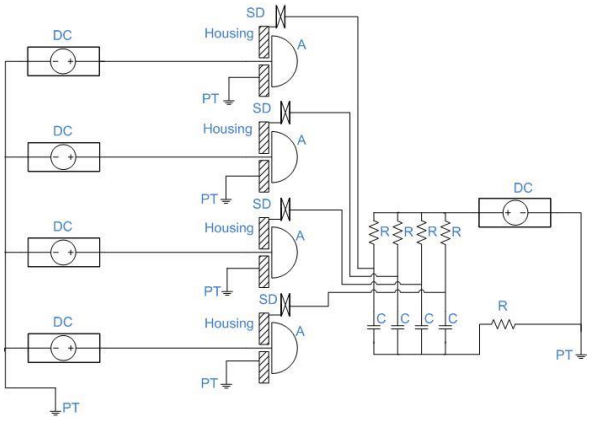

Fig. 4. Electrical circuit diagram. All PSs negative poles are connected to the AUG central grounding point (PT). GD Housing is electrically connected to the vacuum vessel and SD negative pole. Positive terminal of GD PS is connected to the Anode (A). RC elements ensure mutual decoupling and stabilization of SD current.

Following miscellaneous consideration (separate PSs for each SD, usage of high voltage switches for on/off etc.) the decision comes to power the four SDs commonly by one new PS (FUG 2800-6500 max. output current 400 mA, max. output voltage 6.5 kV).

Embedded in the PLC of the AUG gas inlet system, the four GD PS as well as the SD PS can be switched on/off and controlled giving the set-point and reading the actual values for voltage and current. Thereby a completely automated ignition of GD is realised with integrated safety functions.

3.4 GD cabling

For ensuring high level of technical safety the GD high voltage cabling was newly installed from the control cabinets of the PSs to the contact protected electrical feedthroughs (SHV electrical connector) into the vacuum vessel. Each of the cable pairs (GD-electrode, SD) of type RG59 was laid additionally in an armoured conduit to optimize the security of personnel.

4. GD starting behaviour

The procedure for a GD begins with increasing the pressure inside the vacuum vessel by opening the inlet valve of the required gas species (e.g. He or D_2). After attaining a stable pressure of $\approx 4 \cdot 10^{-1}$ Pa in the vacuum vessel the four PSs powering the GD anodes are started to a set-voltage of 1800 V. With a 50 ms delay the PS of the SDs is turned on. As the capacitors have to be charged the voltage ramps up slower. Depending on gas species and condition of the PFCs surface discharge is usually sufficiently strong at a voltage of less than 2.5 kV to produce enough free charge carrier to ignite the GD. Virtually instantaneously current flow begins and GD burning voltage adjusts itself because of the current-limiting mode of the PSs (see Fig. 5). PS of SD is switched off with a time delay of 75 ms after GD ignition.

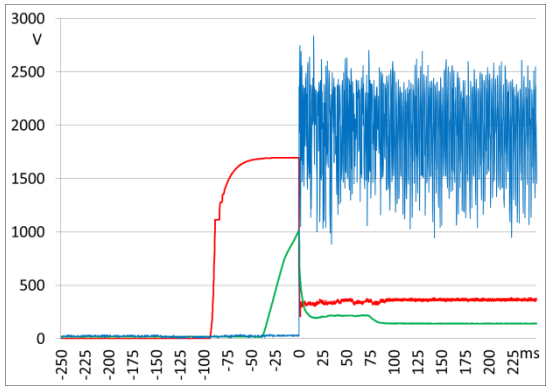

Fig. 5. Start-up behaviour of a GDC in He with SD. Electrode voltage (red) and current (blue), starting device voltage (green).

Numerous tests and operational experience have proven that reliable ignition of GD is nearly always within a period of less than 100 ms after starting the PS of the SDs. Thus it makes it possible to start and stop GDC also for short periods of time and in a pulsed mode operation.

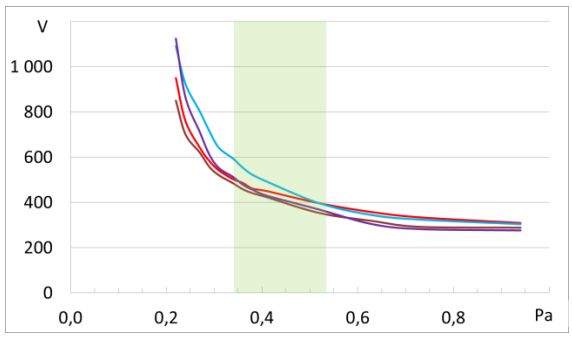

Fig. 6. Glow potential – pressure curve of the 4 GD anodes at a GDC in He. Normal operation pressure indicated in green.

The glow potential vs. pressure curves of the GD electrodes (measured in individual operation) show stable GD conditions (Fig. 6) and the characteristics of all 4 anodes are almost similar. For pressures over $7 \cdot 10^{-1}$ Pa hollow cathode discharge may arise. Therefore at AUG GD is usually operated in a pressure range from $3 \ldots 5 \cdot 10^{-1}$ Pa. At these pressures ignition of GD without using the SDs wouldn't be possible even using GD PSs with much higher voltages than the available 2 kV.

5 GDC cleaning efficiency

As already described, GD in a metal wall device may result in loading of the wall with the working gas [12]. As this effect is proportional to time, it is advantageous to minimize the duration. Typical behaviour of GD is that especially within the first seconds very much adsorbed gas is released from the walls. This leads to a strong enrichment of the operating gas with the released species. During GD these impurity gases are re-implanted in the wall-materials partially deeper than they have been before [13]. This circumstance effects in a balance of removing and implanting impurities after a certain time of continuous GDC and thereby to a loss of efficiency averaged over the GD period. A practicable alternative to a continuous GDC may be a discontinuous operation where the GD is intermittent by a purge phase within the polluted gas is rinsed out of the vessel to start the next GD pulse with less polluted gas. This approach has proven its worth at ion cyclotron wall conditioning (ICWC) were short ICWC discharges were followed by 1…10 s of pumping time [14].

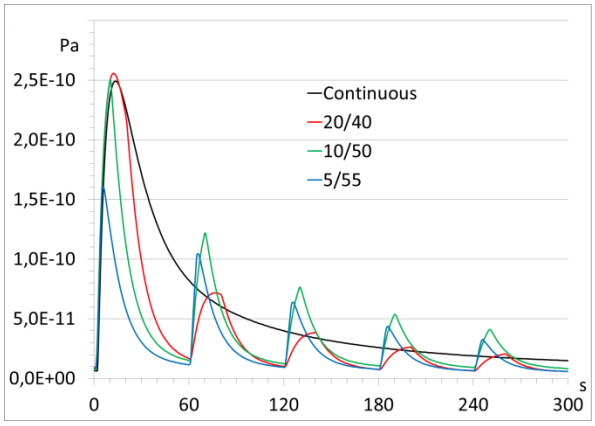

Fig. 7. RGA analysis of Ar partial pressure course during different scenarios of GDC. Continuous GDC (black) and pulsed GDC with GDC/purge ratio 20 s/40 s (red), 10 s/50 s (green), 5 s/55 s (blue).

For validation of the effectiveness of this approach also with GDC, tests have been done in AUG. The examinations were done after four days without plasma experiment operation and hence relatively clean vessel walls. To ensure comparable conditions the vessel walls were preparatory loaded with Argon (Ar) during a 2 min continuous GD in Ar before each of the GDC experiments. Cleaning efficiency was determined by mass spectroscopy analyses (RGA) whereby the partial pressure of the atomic weight of Ar (40) was observed with quadrupole mass analysers (QMS, Hiden HALO 201-RC). The QMS was operating in peak jump mode with only a few masses recording to reduce sampling time to about 1 s. The amount of removed Ar is a measure to compare the relative cleaning efficiency of the different kind of GDCs, whereby other appearing gas species have not been taken into account.

After each Ar loading one 5 min continuous GDC and three different pulsed GDCs with a GDC/purge ratio of 20 s/40 s, 10 s/50 s and 5 s/55 s were carried out in He. Each of them consists of five pulses and thereby total time duration of 5 min.

The partial pressure of Ar decreases in all of the GDC-scenarios over the time (Fig. 7). During the pulsed GDCs it is obvious that for short GDC pulses (5 s…10 s) the amount of released gas increases with the lengths of time (blue and green curve). During the longer 20 s GDC (red curve) desorbed Ar is re-implanted and thereafter bounded more stable on the walls. Consequently proportion of Ar in residual gas is less and therefore quantity of removed gas as well. Furthermore it is obvious that the pumping down time for the released impurities (Ar) is less than 60 seconds.

The comparison of the efficiency of GDC is represented by the integral of the partial pressure for the period of time (Fig. 8). If the amount of the removed Ar is normalized to the individual time of GDC, it appears that pulsed GDC with a ratio of 10 s/50 s is most efficient. This mode of operation removes about 70% of the Ar compared to continuous GDC in only 50 s total time of GDC compared to 300 s in continuous GDC. This shows that only 17% of GDC He implantation compares to 70 % removal of the adsorbed Ar. For this reason the pulsed operation offers a 4.4 times higher removal rate for each He ion compared to continuous GDC.

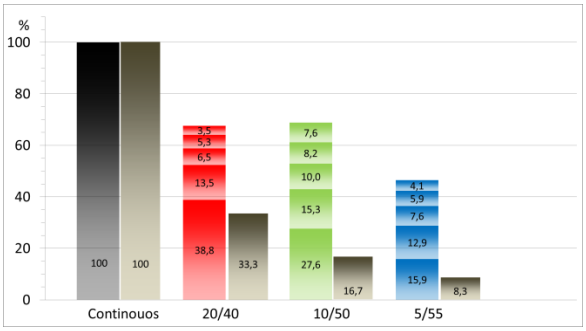

Fig. 8. Normalized integral of total removed Ar compared to the normalized desorbed He (brown bars) for the different kinds of GDC.

For this reason in-between plasma discharges GDC in AUG is currently done in pulsed mode with a GDC/purge ratio of 10 s/50 s.

Acknowledgement

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