NOVEL APPROACH OF PULSED-GLOW DISCHARGE WALL CONDITIONING IN ADITYA UPGRADE TOKAMAK


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Abstract

In ADITYA Upgrade Tokamak, glow discharge wall conditioning (GDC) is performed regularly during the high-temperature plasma operation cycle using Hydrogen (H) and Helium (He) gases. H GDC is carried out after plasma operation for long durations (5 to 12 hours) on every plasma operation day in automatic mode to control Oxygen [O] and Carbon [C] containing impurities. This leads to high retention of H gas on Graphite limiter plates and Stainless Steel (SS) vessel wall. Subsequently, high H outgassing rate requires increased pumping time and high H recycling during plasma discharges affect the plasma performance in respect to H fueling control of the plasma. Intermittent He GDC for shorter duration can be used to decrease the H retention mainly in graphite wall by ion-induced desorption and sputtering phenomena. However, the high sputtering yield and deep penetration properties of He ions lead to high He retention in graphite and metallic walls. The removal of Helium from the limiter and wall is more difficult than H due to its properties of non-reactive, hard-to-trap, vacuum pumping limitation etc. To overcome above-mentioned issues with extended H GDC, a new approach involving Pulsed Glow Discharge Wall Conditioning (P-GDC) has been introduced in Aditya-U tokamak to reduce the residual Hydrogen and Helium concentration in SS vessel walls and graphite limiter plates. It has been observed earlier with continuous GDC that the impurity removal rate is usually high in initial few seconds of GDC operation. The initial high reaction rate is due to the reaction of working gas ions with loosely bound outer most monolayers species. The removal rate then decreases exponentially as hard bonded O and C containing impurities come out slowly. Moreover, the released impurity gases are re-implanted in the wall materials partially deeper in presence of continuous GDC that they have been in its absence. Thus overall impurity removal rate decreases exponentially with time in presence of continuous gas feeding of working gas at high pressure in typical continuous GDC. Initiation of the glow discharge needs filling of H gas at high pressure ~10^2 mbar and ~1 kV biasing voltage between the electrodes and vessel in Aditya Upgrade GDC. In case of pulsed GDC the gas needs to be injected in pulsed mode and the discharge needs to be initiated during every pulse of gas-feed. Therefore in P-GDC, to facilitate the fast initiation of discharge, a source of free of electrons has been introduced in the vessel. A fast feedback pulsed gas-fueling control system and electrons emission system has been developed to initiate glow discharge in each gas-feed pulse at various operating pressure 1 x 10^4 mbar and above in presence of an applied DC voltage. The different Pulsed GDC experiments have been carried out with H, He, Ar as working gases and the results are compared with traditional continuous GDC. The series of experiments have been performed to optimize beneficial wall conditioning for plasma operation. The design, development, operation and results of Pulsed GDC has been described in this paper in details. The effect of P-GDC on plasma discharge performance is also reported in this paper.

1. INTRODUCTION

ADITYA Upgrade, ohmically heated mid-sized tokamak, has been upgraded in double null divertor configuration. The major structural modification from ADITYA to ADITYA Upgrade tokamak is replacement of old rectangular cross section vacuum vessel by new circular cross section vacuum vessel to accommodate additional six divertor (poloidal) coils in space between the new vessel and the old structured toroidal field coils without the changing the tokamak parameters as major radius (R0 = 0.75 m) and minor radius (a = 0.25 m) [1]. Additionally, the in-vessel structure of Graphite first wall material has been added in upgrade tokamak as inner toroidal limiter, two outer poloidal limiters, two poloidal safety limiters, four toroidal divertor plates. This increases the total surface area of in-vessel components with Graphite material. Due to porous structure of Graphite, the fuel gases as Hydrogen and Helium retention stays potentially high.

In ADITYA Upgrade Tokamak, glow discharge wall conditioning (GDC) is performed regularly during the high-temperature plasma operation cycle using Hydrogen (H) and Helium (He) gases. H GDC is carried out after plasma operation for long durations (few hours) on every plasma operation day in automatic mode to control Oxygen [O] and Carbon [C] containing impurities. This leads to high retention of H gas on Graphite limiter plates and Stainless Steel (SS304L) vessel wall and in-vessel components. Subsequently, high H outgassing rate requires
the long pumping time and the high H recycling during plasma discharges affect the plasma performance in respect to H fueling control of the plasma. Intermittent He GDC for shorter duration can be used to decrease the H retention mainly in graphite wall by ion-induced desorption and sputtering phenomena [2]. However, the high sputtering yield and deep penetration properties of He ions lead to high He retention in graphite and metallic walls. The removal of Helium from the limiter and wall is more difficult than H due to its properties of non-reactive, hard-to-trap, vacuum pumping limitation etc.

To overcome above-mentioned issues with extended or continuous H GDC, a new approach involving Pulsed Glow Discharge Wall Conditioning (P-GDC) has been introduced in Aditya-U tokamak to reduce the residual Hydrogen and Helium concentration in SS vessel walls and graphite limiter plates. It has been observed earlier with continuous GDC that the impurity removal rate is usually high in initial few seconds of GDC operation [3]. The initial high reaction rate is due to the reaction of working gas ions with loosely bound outer most monolayers species. The removal rate then decreases exponentially as hard bonded O and C containing impurities come out slowly. Moreover, the released impurity gases are re-implanted in the wall materials partially deeper in presence of continuous GDC that they have been in its absence [4]. Thus overall impurity removal rate decreases exponentially with time in presence of continuous gas feeding of working gas at high pressure in typical continuous GDC.

The fast initiation of the glow discharge needs filling of H gas at high pressure ~ 10^2 Torr with ~1 kV applied biasing voltage between the electrodes and vessel in Aditya Upgrade GDC. After glow discharge generation, the operating fuel pressure is decreased and set in ~ 10^3 Torr range. In case of pulsed GDC the gas needs to be injected in pulsed mode and the discharge needs to be initiated during every pulse of gas-feed at operating pressure ~ 10^4 Torr without increasing the fuel pressure up to ~ 10^5 Torr. Therefore in P-GDC, to facilitate the fast initiation of discharge at GDC operating pressure, a source of free of electrons has been generated in the vessel using pre-ionization filament system.

The different Pulsed GDC experiments has been be carried out with mainly H, He, Ar as working gases and the results are compared with traditional continuous GDC. The relative levels of impurity species such as oxygen and carbon contained impurities are analyzed using residual gas analyzer. The series of experiments has been performed to optimize beneficial wall conditioning for plasma operation. The design, development, operation and results of Pulsed GDC have been described in details. The effect of P-GDC on plasma discharge performance is also reported in this paper.

2. EXPERIMENTAL SETUP

The GDC system of Aditya consists of two ultra-high vacuum bellow-driven movable electrodes placed at the center of the vessel at two diametrically opposite toroidal locations from top of the machine [5], positively biased, and act as anodes. The vacuum vessel is kept as negative potential act as a cathode. The electrodes are powered by a 1000 V, 6 A dc power supply. In Aditya Upgrade, the both anodes are operated remotely by electro-pneumatic system to position at the vessel center and mid plane without disturbing the electrical connections of the tokamak power systems. Thus GDC can be carried out in between plasma operation.

A fast feedback gas-fueling control system has been developed for continuous, pulsed, controlled gas fueling in various wall conditioning procedure of Aditya Upgrade like GDC, ECR-DC, and Ohmic-PDC [6]. In this system, the piezo valve (Maxtec. MV-112) is controlled by developed hardware, feedback gauge controller (Granville Philips GP358) and developed LabView program. As a major advantage, the fueling set (working) pressure is achieved and controlled within few seconds by this system.

For P-GDC, the electrons emission system has been developed to initiate glow discharge in each gas-feed pulse at various operating pressure 1 x 10^4 Torr and above in presence of an applied DC voltage. The tungsten filaments have been installed at various inner locations of the vessel. The vessel is set positive potential with respect to the filaments using bias power supply to emit electrons. A filament power supply (0-30 A, 0-30 VDC) and a bias power supply (0-300 V DC, 0-1 A) are used to control and generate electrons. The source of electrons in vacuum vessel is beneficial to generate discharge between anode and cathode at low working pressure and low voltage. Thus in pulsed GDC, the precise control of the emission of electrons in the vessel is basic and essential technique to generate discharge in the each applied gas pulses of working pressure.
In Aditya upgrade, the fast feedback gas fueling system and the electron emission system are installed and tested successfully for pulsed GDC experiments. The glow discharge has been initiated within 3 seconds at the minimum operating pressure $2 \times 10^{-4}$ Torr with support of electron emission control and fast feedback fueling.

Glow detector system is used to monitor glow availability and glow intensity in the Labview program and near tokamak machine area. The photo resistors are used as sensors for glow detector hardware and installed on the viewport of the tokamak vessel.

Fig. 1 describes the data acquisition and gas-feed and filament control system in GUI program. The program is developed using LabVIEW. Various parameters are given in GUI to control the experiment requirement like fill pressure setting, safe pressure limit, selection of feedback gauge, pulsed GDC On/Off time with no. of cycles, response time, filament timer, record data period etc. In GDC, mainly one pumping line is opened out of four pumping lines of the vessel. In Aditya Upgrade, the vessel is evacuated through four pumps as two TMPs (Pfeiffer Hipace 2300) and two Cryo pumps (CVI Torr TM250) and the vessel isolated by four 250 CF electro-pneumatic valves (VAT make). In GDC, a TMP-1 system pumps the vessel through pumping line-1. As mentioned in Fig.1, the three bayart-alpert type gauges are used in GDC as, IG-1 LH (LH make IM210D gauge) and IG-1 GP (Granville Philips make gauge GP358) installed in pumping line-1 and the IG-5 (Pfeiffer make TPG261) installed on the vessel. The RGA (SRS make RGA 200) is installed at proper location near the TMP-1 pump to measure partial pressure of different gas species during GDC with high pressure operational limit of RGA as $10^{-4}$ Torr.

![FIG. 1. Developed Data Acquisition and Control program in GUI for Pulsed GDC and Continuous GDC Operation Remotely.](image)

### 3. PERFORMANCE AND RESULT

The glow discharge creation in pulsed mode operation was the main challenge in the P-GDC with low working pressure of Hydrogen as $2 \times 10^{-4}$ Torr. The filament pre-ionisation system and the fast feedback gas-feed system provide the great support to initiate glow at working pressure. After P-GDC is established well in Aditya-U tokamak, the comparison of P-GDC with traditional continuous GDC (C-GDC) was carried out. First, the effectiveness of P-GDC was observed using Hydrogen for Oxygen (O) contained and Carbon (C) contained impurities separately. The Hydrogen removal by Helium fuelled GDC was also compared with P-GDC and C-GDC.
3.1. Comparison of C and O-contained impurity removal by H fuelling GDCs

Under the same vessel condition of water vapour as main impurity source, the P-GDC and C-GDC were carried out for few minutes with fill H₂ pressure $2 \times 10^4$ Torr, discharge current 0.6 Amp. As shown in fig.2 region A, the water vapour partial pressure is equal as $1.8 \times 10^{-7}$ Torr before gasfeed and $7.0 \times 10^{-7}$ Torr during gasfeed in both P-GDC and T-GDC. The region B indicates the glow discharge is started in pulsed and continuous mode fuelling. During GDC in region C, in P-GDC, 5 discharge pulses with 2 minutes (mins) on time and 3 mins off time were generated. While C-GDC were performed continuously with time period 25 mins. As experimental observation in fig.2, the water vapour was removed in P-GDC in 5 cycles of discharges from $9.0 \times 10^{-8}$ Torr to $1.6 \times 10^{-8}$ Torr as reduction in factor 5.6. While in C-GDC, the H₂ gas was fuelled into the vessel within 10 mins that is equal to the total fuelled gas in the P-GDC. The water vapour was reduced in factor 2.8 in C-GDC that is half reduction compare to P-GDC. In C-GDC, the total 25 mins of glow discharge cleaning was required to remove the water vapour in reduction factor 5.6, while this factor was achieved in 10 mins glow discharge cleaning in the P-GDC. Thus limited fuelling of Hydrogen gas in P-GDC provides tremendous reduction of hydrogen fuelling gas load as in factor 2.5 compare to C-GDC.

The other O-contained impurity species like carbon monoxide (CO) and carbon dioxide (CO₂) were found in high concentration during both types of GDC, when the oxygen, water vapour were dominant source in the vessel. As experimental observation in fig.3, the CO partial pressure is equal as $7.0 \times 10^{-8}$ Torr before gasfeed and $2.5 \times 10^{-8}$ Torr during gasfeed in both P-GDC and T-GDC. The carbon monoxide was removed in P-GDC in 5 cycles of discharges from $9.0 \times 10^{-3}$ Torr to $4.5 \times 10^{-3}$ Torr as reduction in factor 2.0. While in C-GDC, the H₂ gas was fuelled into the vessel within 10 mins that is equal to the total fuelled gas in the P-GDC. The CO was reduced in factor 1.3 in C-GDC that is effectively less reduction compare to P-GDC. In C-GDC, 25 mins continuous cycle of glow discharge cleaning removed the CO $7.0 \times 10^{-9}$ Torr to $4.5 \times 10^{-9}$ Torr as in reduction factor 1.6 that is also less compared to 10 mins glow discharge cleaning in the P-GDC. In fig.3, CO₂ partial pressure is equal as $1.0 \times 10^{-9}$ Torr before gasfeed and $7.0 \times 10^{-9}$ Torr during gasfeed in both P-GDC and T-GDC. The carbon dioxide was removed in P-GDC in 5 cycles of discharges from $1.5 \times 10^{-3}$ Torr to $4.5 \times 10^{-3}$ Torr as reduction in factor 3.3. The CO₂ was reduced within 10 mins as factor 2.0 in C-GDC that is effectively less reduction compare to P-GDC. In C-GDC, 25 mins continuous cycle of glow discharge cleaning removed the CO₂ $1.2 \times 10^{-7}$ Torr to $4.5 \times 10^{-8}$ Torr as in reduction factor 2.7 that is also less compared to 10 mins glow discharge cleaning in the P-GDC. The low background partial pressure of H₂, CO, CO₂ after GDC completion indicates more impurity released in P-GDC compare to C-GDC. In P-GDC, $9.7 \times 10^{31}$ Hydrogen particles were injected in 5 cycles that is 2.5 times lesser than particles injected in C-GDC of 25 mins.

![FIG. 2. Removal of water vapour (H₂O) by P-GDC and C-GDC using Hydrogen as working gas with same initial vessel condition of water vapour in both types of GDCs.](image-url)
3.2. Comparison of C-contained impurity removal by H fuelling GDCs

In Aditya-U, the carbon contained impurity is seen high in GDC and Tokamak plasma due to high surface area (20,000 cm$^2$) of the first wall components of the material Graphite as the inner toroidal and outer poloidal limiters, divertor plates, and safety limiters [7]. After removal of O-contained impurity in form of H2O, the C-contained impurity like CH4, CO, CO2, various hydro-carbons are found more in glow discharge cleaning. In Aditya-U For only C-H impurity, the CH4 is observed maximum compared to other hydro-carbon species. The other C-H impurity like CH3, C2H3, C3H2, CH3CH2 and C3H5 are also observed significantly in Hydrogen GDC. For comparison, the same vessel condition of CH4 as main impurity was chosen for the P-GDC and C-GDC.

**FIG. 3. Removal of carbon monoxide (CO) and carbon dioxide (CO$_2$) by P-GDC and C-GDC using Hydrogen as working gas with same initial vessel condition of CO and CO$_2$ in both types of GDCs**

**FIG. 4. Removal of Methane (CH$_4$) by P-GDC and C-GDC using Hydrogen as working gas with same initial vessel condition of CH$_4$ in both types of GDCs**
Same as above mentioned, the parameter were set for both types of GDCs as fill H$_2$ pressure 2 x 10$^{-4}$ Torr, discharge current 0.6 Amp. As shown in fig.4, the CH$_4$ partial pressure is almost equal as 1 x 10$^{-6}$ Torr before gasfeed and 5.0 x 10$^{-8}$ Torr during gasfeed in both P-GDC and T-GDC. In P-GDC, 5 discharge pulses with 2 minutes (mins) on time and 3 mins off time were generated. While C-GDC were performed continuously with time period 25 mins. As experimental observation in fig.4, the CH$_4$ was removed in P-GDC in 5 cycles of discharges from 1.0 x 10$^{-6}$ Torr to 4.0 x 10$^{-7}$ Torr as reduction in factor 2.5. While in C-GDC, CH$_4$ was reduced in factor 2.0 within 10 mins and 2.3 for 25 min operation. The other two hydrocarbon C$_2$H$_3$ (mass # 27) and CH$_3$CH$_2$ (mass # 29) were observed significantly with other hydro carbons C$_2$H$_2$ and C$_3$H$_5$ in both types of GDCs.

As shown in fig.5, mass 29 is reduced in factor 2.7 in P-GDC's 5 cycles (10 min) and 2.0 in C-GDC's 25 min. The mass 27 is reduced in factor 4.0 in P-GDC's 5 cycles (10 min) and 3.1 in C-GDC's 25 min. Thus Hydrogen fuelling P-GDC is more effective to remove the O, C and HC-contained impurity compare to C-GDC with limited Hydrogen gas injection.

**FIG. 5.** Removal of other dominant hydro-carbon species Mass # 27 (C$_2$H$_3$) & Mass # 29 (CH$_3$CH$_2$) by P-GDC and C-GDC using Hydrogen as working gas with same initial vessel condition of CH$_4$ in both types of GDCs

### 3.3. Comparison for Hydrogen removal by Helium fuelling GDCs

In Aditya-U, as mentioned above high surface area of Graphite affects the plasma discharge by hydrogen recycling, which is generated by the porosity of first wall Graphite with large surface area. During H$_2$ continuous GDC, the high gas load of Hydrogen diffuse and trap in the Graphite. Thus Helium GDC is carried out periodically to remove Hydrogen by Ion induced desorption with limited quantity of Helium. But, Continuous Helium GDC is also increased gas load of Helium in In-vessel components. The P-GDC is also implemented for Helium fuelling and compare with C-GDC in Aditya-U. The parameter were set as discharge current 1.0 A with 5.5 x 10$^{-4}$ Torr Helium pressure in both types of GDCs. As shown in fig.6, The 5 cycles of P-GDC (2 min on, 3 min off) reduced the Hydrogen from 5.5 x 10$^{-4}$ to 3.3 x 10$^{-5}$ as reduction factor 1.7. The same reduction factor as 1.6 was achieved in 25 mins of C-GDC with 2.5 times high Helium Fuelling compare to P-GDC.
3.4. Effect of P-GDC in Tokamak Plasma Discharge

In Aditya-U, regular continuous GDC is carried out in the evening after tokamak plasma shots completion. The long hour Hydrogen Fuelling GDC increase the base level of residual Hydrogen as 1.0 to 3.0 x 10^{-7} Torr on next day plasma operation. In addition, the trapped Hydrogen is released during high temperature plasma discharge as Hydrogen recycling, which is observed in spectral line of H-alpha. The Hydrogen residual level was reduced as < 5 x 10^{-8} Torr due to P-GDC. That effect is also observed in H-alpha line spectrum. The initial study of P-GDC with Argon-Hydrogen (50:50) mixture gases was carried out on the cleaned vessel. Here cleaned vessel means the ultimate vessel conditioning achieved due to Hydrogen GDC for major impurity source of carbon species as CH_{4} and CO_{2}. In Ar-H mixture glow cleaning in pulsed mode, the CH_{4} minimum (or cleaning saturation) level was improved from 2.5 x 10^{-7} to 1.5 x 10^{-7} Torr in short period. Same as, the CO_{2} minimum level was improved from 3 x 10^{-7} to 2.0 x 10^{-7} Torr. Thus the saturation level of cleaning for Hydrogen GDC was improved due to Ar-H (50:50) P-GDC for short period like (10 cycles of 2 min). The combined effect of P-GDC with H_{2} and Ar-H_{2} were observed in high temperature plasma shots with low hydrogen recycling by H-alpha and impurity line reduction in C-III and O-II lines. The detail study of mixture P-GDC is under progress.

4. CONCLUSION

The glow discharge initiation at Hydrogen working pressure as 2 x 10^{-4} Torr was major challenge for pulsed GDC operation in Aditya upgrade tokamak. The developed fast feedback gas fuelling system and pre-ionization filament system had supported and realized the pulsed discharge initiation less than 3 sec from base pressure level to controlled working pressure. After series of experimental parameters of Pulsed GDC, the effective data were taken with 2 min on time and 3 min pumping time for impurity. The recombination and ionization of released impurity species from the vessel wall were minimised in this P-GDC with low pressure discharge and extended pumping time. The Hydrogen is major source after sufficient baked stainless steel vacuum vessel in 10^{-9} Torr pressure. The P-GDC operation of wall conditioning provides limited gas injection and more impurity removal compare to traditional C-GDC. That is effective to maintain the vessel pressure low and limited monolayers formation. The initial study of P-GDC in Aditya-U gives the significant effect of H_{2} P-GDC on water vapour as 2 times better removal rate compare to C-GDC with same gas injection. In Addition, H_{2} P-GDC is more effective for CO and CO_{2} as 1.5 times better removal rate than C-GDC. While Aditya-U vessel is sufficiently cleaned, the major impurity source are hydro-carbons impurity, which are released and cleaned up to saturation level by H_{2} P-GDC within 10 min pulsed discharge operation and 25 mins C-GDC operation. Same as, the Hydrogen is reduced at particular level by Helium pulsed GDC with in 10 min pulsed discharge operation and this particular level is achieved by C-GDC in 25 min discharge operation. The initial study of P-GDC provides the new way of wall conditioning in place of traditional glow discharge cleaning for fusion experiments.
REFERENCES


