Influence of Wall Conditioning on ADITYA Plasma Discharges

R L Tanna, K A Jadeja, S B Bhatt, P S Bawankar, C N Gupta, Y S Joisa, P K Atrey, R Manchanda, Nilam Ramaiya, J Ghosh, D Raju, P K Chattopadhyay, R Jha and the ADITYA team

Institute for Plasma Research, Bhat, Gandhinagar-382 428, Gujarat, India.

Email: rakesh@ipr.res.in, rtan.ipr@gmail.com

Abstract. ADITYA (R0 = 75 cm, a = 25 cm), an ohmically heated circular limiter tokamak is regularly being operated to carry out several experiments related to controlled thermonuclear fusion research. In recent operational campaign, various experiments have been carried out to enhance the discharge performance as well as improve the plasma parameters. A comparative plasma discharges study with SiC and Graphite limiter was carried out to increase the plasma heating and reduce runaways. Excellent plasma heating has been observed in many discharges using Graphite limiter. Good repeatability of low hard X-rays, high temperature discharges was obtained. The control of plasma impurities and hydrogen recycling is very much essential for high performance discharges. The wall conditioning in ADITYA tokamak is carried out by hydrogen glow discharge cleaning (GDC), Pulse discharge cleaning and electron cyclotron resonance (ECR) discharge cleaning techniques with and without lithium wall coating. GDC assisted Lithiumization was found to be the most effective technique for substantial reduction in Hα and low Z (CIII & O-I) impurities. The partial pressure of mass number 18 (H2O) and 28 (N2/C2H4/CO) were regularly monitored before plasma discharge operation. Furthermore, experiment on optimization of pulse gas feed was helped in reducing wall loading and recycling. However, hard X-rays suppression with the application of multiple gas puff has been successfully achieved during negative converter operation, which led to the extension of plasma pulse length up to ~ 250 ms. All the supporting facts and operation aspects are reported.

1. Introduction

ADITYA is ohmically heated limiter based, moderate size tokamak and is regularly being operated with the transformer converter power supply [1]. During recent operation campaign, the toroidal field of (Bt = 0.75-0.84 T), the peak loop voltage of (VL ~ 20 V), the plasma current of (Ip = 70- 90 kA) and duration of 100-270 ms have been achieved in ADITYA tokamak. The line average electron density (n_e) is in the range of 1.5–2.0 x 10^{13} cm^{-3} and the electron temperature (T_e) is in the range of 300-600 eV. The plasma is generated in a stainless steel vessel evacuated to a base pressure of 1.0 x 10^{-7} torr. The working plasma fueling gas is hydrogen filling at a pressure of 8 x 10^{-5} to 1 x 10^{-4} torr. The pre-ionization filament kept on with filament current 19 A and bias voltage 150 V during the plasma experiments.

Recent upgradation in ADITYA performance has been carried out with various experiments including recycling study with SiC and graphite limiter, low hard X-ray, high temperature plasma discharge operation, application of gas-puff on plasma discharges and long pulse plasma discharges.
with negative converter have been performed to enhance the plasma discharge performance. In past, the discharge failure has been restricted and the repeatability as well as reliability of successful plasma discharges has been obtained after optimizing the method of gas fuelling [2].

2. Experimental set-up

In ADITYA, all the magnetic coils are powered by computer-controlled thyristor based pulsed power supply and discharge data are stored in CAMAC based data acquisition system. The main set of diagnostics used in these experiments are namely, Rogowski coils for plasma current and VF current measurements, voltage loop for loop voltage measurements, Optical detectors for impurity radiation including Hα measurements, microwave interferometer for electron density, Scintillation detector with NaI (Tl) source for hard X-ray measurements, soft X-ray detectors for electron temperature measurement, magnetic probes garland for magnetic fluctuation measurement, impurity radiation power using bolometry and the position probes are used for plasma position measurements.

2.1 Gas fueling systems at ADITYA tokamak

The Piezo-electric valve is installed to control the fuel gas pressure. Two different methods have been used for gas fueling viz. static (continuous) gas feed and pulsed (Pre-fill) gas feed [3]. In continuous gas feed, the fuel gas is introduced in the vessel by applying DC voltage just few seconds before the loop voltage is established. Whereas, in the pulsed gas feed, a square pulse is applied through pulse generator with the time-delay of few ms before the loop voltage is established.

2.2 Wall conditioning techniques at ADITYA tokamak

Various wall-conditioning techniques are used all over the world in tokamak operation to reduce the impurity influx from the wall and enhance the plasma performance. To achieve better wall conditioning in ADITYA, DC glow discharge cleaning (GDC), pulse discharge cleaning (PDC), electron cyclotron resonance (ECR) discharge cleaning as well as superimposing a PDC on the ECR background techniques [4] with and without lithium coating are carried out with hydrogen plasma as per experimental requirements. The partial pressure of various Mass numbers like O₂, CO, N₂, CH₄, and H₂O etc. were monitored with quadruple mass analyzer (QMA).

GDC system consists of two UHV bellow driven movable electrodes, placed diametrically opposite at the center of the vessel [5], which have a positive potential act as anodes and vacuum vessel being kept as negative potential act as a cathode. The discharge voltage is about 350 V to 400 V and discharge current is of the order of ~3.5 A. The GDC is carried out at higher hydrogen gas pressure of ~8 x 10⁻⁴ to 1 x 10⁻³ torr and automated for maximum 12 h in absence of toroidal magnetic field. The electron temperature during GDC is of the order of ~5 eV. During PDC, the ohmic coils are powered by a capacitor bank power supply to generate the loop voltage required for the gas breakdown. The toroidal field is of the order of 500 G during combined ECR + PDC, whereas it is 900 G for alone PDC. The hydrogen gas is fueling at the pressure of ~2 to 3 X 10⁻⁵ torr. The measured electron density is ~1 x 10¹¹ cm⁻³. The pulse repetition rate during PDC is ~ 900 pulses/h of 4 ms duration. Microwaves of 2.45 GHz frequency is produced by a Magnetron of 1 kW power level are launched towards the plasma chamber during ECR. The anode current is 200 mA. The ECR operation duty cycle is about 66%. The maximum electron density (measured using Reflectometry) during combined ECR+PDC is of the order of 6 x 10¹¹ cm⁻³. The effect of solid target Lithiumization has been performed in ADITYA with various methods. Initially, two lithium rods of diameter 12 mm, toroidally 180° apart, were inserted at 20 mm inside the plasma volume. The evaporation of lithium in vacuum vessel has been done with ECR, PDC and GDC as well as with actual tokamak discharges.

2
3. Experimental results and Discussions

3.1 Recycling study with SiC and Graphite limiter

The optimal choice of limiter material for plasma-facing components have major role on plasma discharge behavior and it was experimentally studied in ADITYA tokamak. Similar studies have been reported in TCA, JET-2 [6] and ALCATOR C tokomaks [7]. Silicon Carbide (SiC) coated graphite limiters have been chosen in ADITYA being low Z materials, higher thermal conductivity and lower vapor pressure. This includes lower chemical and sputtering yield, better oxygen gettering and lower hydrogen recycling. Till Dec. 2009, ADITYA has been operated with poloidal graphite limiter with radius of ~ 25 cm. The main problem with this limiter was that discharges were not consistent at higher operating pressure ($\geq 1 \times 10^{-4}$ torr) and lower ($E/P \sim 400$ V cm$^{-1}$ torr$^{-1}$) because of more carbon impurity and its insufficient burn through in the start-up. Therefore, the replacement of graphite limiter to SiC was envisaged. During vessel opening in Dec. 2009, the SiC limiter was introduced. It consists of 20 nos. of SiC coated graphite tiles mounted on SS support structure in poloidal direction. The limiter radius of ~ 24 cm was kept to increase the gap between vessel wall and limiter. The thickness of SiC coating was about 100 µm [8].

During recent operation campaign (15th October to 3rd December 2010), discharges with SiC coated graphite limiter showed (1) Increase in H$_{\alpha}$ and C-III, O-I impurity line radiation restricts the electron temperature rise (2) Hard X-rays could not be controlled even with maximum gas pressure of $1 \times 10^{-4}$ torr and lowest $E/P$ up to 425 V/torr-cm. This was probably due to the lowering the radius of limiter. Furthermore in last week of Dec 2010, the original graphite limiter of radius ~ 25 cm was installed back to identify the reason. The time evolution of ADITYA discharges comparison between SiC coated graphite and pure graphite limiters for similar operating parameters are shown in ‘figure 1’.

![Discharge Comparision with SiC and Graphite limiter](image)

Fig. 1. Time series of (a) Loop voltage, (b) H$_{\alpha}$, (c) O-I, (d) C-III, (e) Hard X-rays, (f) VF current, (g) plasma current, (h) Radial position (i) Soft X-rays, (j) bolometer (k) electron temperature and (l) Pressure (value x calibration factor 4) with SiC and graphite limiter.

The experimental results show significant reduction in H$_{\alpha}$ and C-III, O-I impurity line radiation signals and huge reduction in hard X-rays (except for first 10 ms) are observed in discharges with graphite limiter. This is also reflected in the plasma current driven by runaways. The excellent plasma heating is observed in many discharges with graphite limiter. The electron temperature goes up to 450 eV for shot 22192 in ‘figure 1’ measured with Soft X-ray diagnostic.

3.2 Low hard X-ray, high temperature plasma operation

In order to obtain low hard X-ray, high temperature discharges with better repeatability, the experiment was carried out with total 25 h of limiter baking at maximum 100$^\circ$ C temperature out of that 12 h limiter baking was carried out with GDC. The variation in plasma electron temperature and wall conditionig progress after installation of graphite limiter is tabulated in Table 1.
### Table 1. The wall conditioning and plasma temperature progress after installation of graphite limiter

| Shot series     | Wall conditioning | Partial pres. (M # 18) (torr) | Partial pres. (M # 28) (torr) | Base Pres. | Electron temp. (eV) |
|-----------------|-------------------|-------------------------------|-------------------------------|------------|---------------------|
| 22124 – 22148   | 12 h GDC          | 6.7 x 10^9                   | 5.6 x 10^8                    | 3.6 x 10^7 | 300                 |
| 22149 – 22172   | 12 h GDC          | 5.8 x 10^9                   | 2.5 x 10^8                    | 3.4 x 10^7 | 400                 |
| 22173 – 22196   | 12 h GDC          | 4.4 x 10^9                   | 2.4 x 10^8                    | 3.1 x 10^7 | 450                 |
| 22210 – 22237   | 12 h GDC          | 4.4 x 10^9                   | 2.1 x 10^8                    | 2.7 x 10^7 | 500                 |
| 22238 – 22263   | 12 h GDC          | 3.0 x 10^9                   | 2.1 x 10^8                    | 2.9 x 10^7 | 600                 |

The time evolution of typical ADITYA discharges for plasma electron temperature progress after installation of graphite limiter is shown in ‘figure 2’.  

In addition to that the ADITYA discharges repeatability was established with the application of fast feedback position control and excellent wall conditioning with graphite limiter backing. We have achieved 13 repeatable discharge of around 100 ms duration with good heating and stable electron temperatures of around 350 eV. The time evolution of typical ADITYA discharges repeatability is shown in ‘figure 3’. The sufficient pumping time was provided between two shots and partial pressure of water vapour and N₂ / CO is monitored before each shot.
3.3 Application of Gas-puff on ADITYA plasma discharges

The behavior of density-limit disruptions caused by different gas fuelling methods like Molecular Beam Injection (MBI), gas-puff (GP) have been already studied in ADITYA tokamak discharges [9]. The edge fluctuation suppression with the application of gas-puff of working gas fuel has also been studied in ADITYA tokamak [10]. Apart from these studies, recently we have studied the runaway suppression by enhancing the line average electron density as well as MHD mode suppression with the application of multiple gas-puff of working gas fuel (hydrogen). The similar experiments on runaways suppression by strong helium gas-puff has been studied in TEXTOR, ASDEX and JET tokamak [11].

The multiple gas-puff is introduced in the vessel by using a Piezo-electric valve (500 SCCM at 100 V). The valve is mounted on the bottom port and located 10 cm radially (on the bottom port) and 90° toroidally from the limiter. The pulse widths timing and voltage level, time (T) for gas-puff to start, number of pulses and the time gap between the pulses were varied with pre-programmed gas-puff according to the discharge requirements. The time evolution of typical ADITYA discharge parameters comparison with and without multiple gas-puff is shown in ‘figure 4’.

![Figure 4](image)

**Fig. 4.** Time series of (a) Plasma current, (b) gas-puff and chord average electron density, (c) Hard X-rays, (d) Mirnov signal and (e) Radial position with & without multiple gas-puff.

Figure 4 shows that in absence of multiple gas-puff (Shot: 22672), Plasma column shifted towards outer wall interacts with impurity that strikes the MHD activities. Mode analysis results describes in ‘figure 5’ shows first m=4 mode, later m=3 that converted into m=2 at the end. Chord average electron density falls, which brings lots of runaways.

![Figure 5](image)

**Fig. 5.** MHD mode analysis with Mirnov signal for shot: 22672 (a) 32 –34 ms, m=4 mode, (b) 46 – 48 ms m=4 mode, (c) 72 –74 ms, m=3 mode and (d) 82 –84 ms m=2 mode.

Hydrogen gas pulse of 10 nos. with typically pulse width of ~ 0.2 ms and amplitude of ~ 100 V at different time interval were introduced in discharge (shot: 22679), which raised the electron density up to maximum of 2.8 x 10^{13}/cc and control MHD activities as well as hard X-rays. Stable plasma equilibrium towards the center was observed in discharge with multiple gas-puffs.
3.4 Pulse length enhancement of plasma current with negative converter operation
In order to increase the volt-sec, ohmic current swing was extended in the negative direction (+11 kA to −7.5 kA) to generate loop voltage up to ~ 275 ms. This will provide constant flattop loop voltage of ~ 2 V during negative converter phase. The maximum discharge duration of ~ 270 ms was obtained through the tuning of operating parameters. The time evolution of ADITYA discharge parameters with negative converter operation is shown in ‘figure 6(a)’. The multiple gas-puff were introduced during the middle of the discharge that enhance the plasma density and helps in control the hard X-ray up to some plasma length is shown in ‘figure 6(b)’. The maximum electron density of the order of 3 x 10¹³ /cc and electron temperature of the order of 500 eV was observed.

The plasma current starts falling during auxiliary phase (~ 100 ms) because of decreasing loop voltage during that phase and remains at lesser value during negative converter phase.

4. Conclusion
In recent operation campaign, ADITYA machine has been successfully operated for various performance improvement experiments. In this article, we have reported some of the relevant results of recent experiments. The experiment on recycling study with SiC coated graphite limiter and graphite limiter, reveals significant reduction in Hα and CIII, O-I impurity line radiation in discharges with graphite limiter. The excellent plasma heating improves the electron temperature up to 500 to 600 eV. Optimal operation parameters tuning, better wall condition and Fast Feedback position control provides excellent repeatability of ADITYA discharges. The runaways present in the discharge are successfully suppressed using multiple gas-puff of hydrogen gas of optimum pulse width at different time interval by enhancing line average electron density. This could also suppress MHD activities and maintains plasma equilibrium towards the centre. The plasma pulse length is enhanced beyond 250 ms with the application of negative converter. The drops in plasma current after 100 ms because of slightly lowering of loop voltages in auxiliary converter phase will be resolved in near future.

Acknowledgement
The author would like to acknowledge Mr. V K Panchal of data acquisition group and Mr. Nirav Mecwan, Mr. Pintu Kumar, Mr. M B Kalal and Mr. D S Varia of ADITYA operation group for their help and support provided during experiments.
References
[1] S.B. Bhatt et al, Ind. j. of Pr. and appl. Phys. Vol. 27, Sept.-Oct. Pg. 710-742 (1989).
[2] R. L. Tanna, et al, 21st Nat. Symps. on Plasma Sc. & Tech., Dec. 19-22, 2006, Jaipur, India.
[3] R.J. Hawryluk et al, J. Nuclear Fusion Vol. 16 (1976), Page. 775-781
[4] Ram Prakash et al, J. Appl. Phys. 97, 043301 (2005)
[5] H.A Pathak et al, J. Nuclear Materials, 220 -222 (1995) 708- 711
[6] Yoshio Gomay, et al, Japan. J. Appl. Phys., Vol. 18, No. 7, July 1979, pp. 1317 -1324.
[7] E. Marmar et al., J. Nuclear Materials 121 (1984) 69 -74
[8] S.B. Bhatt et al, 12th Int. Workshop on PFMC 11 – 14 May 2009, Julich, Germany
[9] S.B. Bhatt et al, Journal of Fusion. Eng. & Design, 75 – 79 (2005), 655 -661.
[10] R. Jha et al, Plasma Phys. Control Fusn. 51 (2009), 095010 (17pp)
[11] H.R.koslowski et al, IPP/FZJ/Julich/Scientific report-2001/Vol.5/page.1-5.