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Plasma production and preliminary results from the ADITYA Upgrade tokamak

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Abstract

The Ohmically heated circular limiter tokamak ADITYA ($R_0 = 75$ cm, $a = 25$ cm) has been upgraded to a tokamak named the ADITYA Upgrade (ADITYA-U) with an open divertor configuration with divertor plates. The main goal of ADITYA-U is to carry out dedicated experiments relevant for bigger fusion machines including ITER, such as the generation and control of runaway electrons, disruption prediction, and mitigation studies, along with an improvement in confinement with shaped plasma. The ADITYA tokamak was dismantled and the assembly of ADITYA-U was completed in March 2016. Integration of subsystems like data acquisition and remote operation along with plasma production and preliminary plasma characterization of ADITYA-U plasmas are presented in this paper.

Keywords: ADITYA-U tokamak, Phase I plasma operation, toroidal limiter, enhanced parameters

(Some figures may appear in colour only in the online journal)

1. Introduction

The ADITYA tokamak ($R_0 = 75$ cm, $a = 25$ cm) with a limiter configuration has been upgraded to ADITYA-U tokamak with an open divertor configuration [1] with divertor plates without any baffle, to support the future Indian fusion program. The main scientific objectives of ADITYA-U are to carry out dedicated experiments relevant for large size fusion machines including ITER, such as the generation and control of runaway electrons, disruption prediction, and mitigation studies, along with plasma position control and confinement improvement studies with shaped plasma. The idea behind upgrading small/medium size tokamaks is to carry out experiments, which because of the risky nature, are rarely and reluctantly carried out in large machines without preliminary studies, such as disruption, runaway studies, etc. The ADITYA-U is designed to produce a circular plasma with plasma current of ~150–250 kA, plasma duration of ~250–300 ms with electron density and temperature in the range of (3–5) × 10^{19} m^{-3} and 500–1000 eV, respectively. Further, it is designed to obtain shaped plasmas with plasma current of ~100–150 kA, elongation $k \sim 1.1$–1.2, and triangularity ~0.45.

The major modification to the existing ADITYA tokamak [2] is aimed at the replacement of the rectangular cross section vacuum vessel with a circular vacuum vessel to accommodate additional poloidal (divertor) coils in the space between the new vessel and toroidal field coils [1]. In order to accommodate the new divertor coils and new circular shaped vacuum vessel, ADITYA has been dismantled up to the base level. The assembly of ADITYA-U was successfully completed in March 2016 including the installation of a new circular shaped vacuum vessel, a new buckling cylinder, refurbished toroidal field (TF) coils (20), TR coils (11), vertical field (BV) coils (4), fast feed back (FFB) coils (4), inner divertor coils (2), outer divertor coils (2), and auxiliary divertor coils (2). Following the successful integrated power testing of magnet coils up to the design parameters, basic diagnostics along with data acquisition systems were installed for the Phase I plasma operation. After the installation of the plasma facing component (PFC) in the new vacuum vessel of ADITYA-U [3], plasma operations were resumed in the upgraded machine in a graphite toroidal belt limiter configuration with hydrogen plasma. The first discharge in ADITYA-U was obtained on December 1, 2016. For several years now, nearly all the experimental work conducted on tokamaks throughout the world—including DIII-D [4] in the USA, JET [5, 6], ASDEX [7] and FTU [8] in the EU, JT60 [9, 10] in Japan, KSTAR [11] and VEST [12] in Korea, ADITYA and SST-1 [13, 14] in India, HL-2A [15], EAST [16] and J-TEXT [17] in China—has been to investigate the optimum operational parameters in the start-up phase. Understanding and optimization of the parameters in the start-up phase is critical not only for the future successful ITER start-up scenario [18], but also for saving the valuable voltage-second (Vs) [19], which prompts more rapid burn-through and ultimately extends the pulse length of the discharge. In a recent Phase I operation, repeatable plasma discharges of plasma current of ~80–95 kA with a duration of ~80–100 ms with a toroidal magnetic field B_ϕ (maximum) ~1 T and chord average electron density of $\sim 2.5 \times 10^{19}\ \mathrm{m^{-3}}$ have been obtained. Later, the discharge duration has been enhanced up to 180 ms with the application of negative converter power supply operation. The discharge of hydrogen gas is initiated using filament preionization and gas breakdown has been obtained in each of ~700 discharges (Phase I) without a single failure in a fill-in pressure range of $(0.8\text{–}2.0) \times 10^{-4}$ Torr. The discharge failures in the current ramp-up phase were mostly due to improper impurity burnouts and have been overcome by extensive wall conditioning techniques such as glow discharge cleaning (GDC) in hydrogen and in the mixture of gases (H_2-Ar, H_2-He) along with intense short plasma pulses in the electron cyclotron resonance (ECR) produced plasma background. The disruptions during the plasma current flat-top due to the sudden growth of magneto-hydro dynamic (MHD) modes are steered through by properly adjusting the ramp rate of the plasma current. The generation of runaway electrons is controlled using high fill-in pressure during the breakdown phase and by suitable external hydrogen gas puffing during the plasma current flat-top. Maximum line-averaged plasma density $\sim 2.5 \times 10^{19}\ \mathrm{m^{-3}}$ and temperature (estimated) >150 eV have been achieved in the discharges.

In this paper we present the results of recent activities on the experimental research of the first production of plasma from ADITYA-U. The experimental set-up is described in section 2, the Phase I operation preparation is discussed in section 3, the main experimental results are discussed in section 4, and the article is summarized in section 5.

2. Experimental set-up

Four pumping lines, two turbomolecular pumps, and two cryopumps were installed on the vacuum vessel to achieve an ultra-high base vacuum. The base pressure of the order of $\sim(2\text{–}5) \times 10^{-8}$ Torr (without baking) has been achieved on a regular basis during the Phase I operation. The in-vessel components such as the toroidal limiter, poloidal limiter, and safety limiter made up of graphite tiles were installed. Extensive wall conditioning techniques such as GDC in H_2 gas and in a mixture of gases (H_2:Ar, H_2:He) along with intense short plasma pulses (capacitor discharges) in the ECR plasma background were carried out on a regular basis before operation. Typical plasma parameters for the discharges presented in this article are B_ϕ ~0.75–1 T, peak loop voltage of ~20–22 V, plasma current of ~80–95 kA, discharge duration of ~ 75–180 ms, chord-averaged electron density (n_e) ~ $(1.5\text{–}2.5) \times 10^{19}\ \mathrm{m^{-3}}$, and edge safety factor q ~ 3–4. The working plasma fueling gas is hydrogen filled at a pressure range of $0.8\text{–}2.0 \times 10^{-4}$ Torr. A piezo-electric valve is installed at one of the bottom ports to control the fuel gas pressure operated in a pulsed (pre-fill) gas feed mode. In the pulsed gas feed mode, a square pulse is applied, 250 ms prior to the loop voltage, through a pulse generator [20]. The discharge is initiated using filament preionization with a filament current of 20 A and bias voltage of 150 V during the experiments. The partial pressures of various mass species like H_2, O_2, CO, N_2, CH_4, and H_2O were monitored on a regular basis with a quadruple mass analyzer (QMA). The multiple H_2 gas puffs were introduced into the vessel by using a piezo-electric valve (500 sccm at 100 V). A programmable pulse generator was used for multiple gas puffs to control the fuel gas. The main set of diagnostics used in these experiments includes magnetic diagnostics such as flux loops, two poloidal arrays of magnetic probes (Mirnov coils) for plasma position measurement, diamagnetic loops, and four internal Rogowski coils. Before starting the experiment the Rogowski coils for plasma current measurements was calibrated accurately within an accuracy of ±0.5%. Apart from magnetic diagnostics, other diagnostics such as spectroscopic, microwave, soft x-ray (SXR) and hard x-ray (HXR) detectors, bolometers, and Langmuir probes were installed for the Phase I operation of ADITYA-U. The locations of the different diagnostics on the vacuum vessel are shown in figure 1.

Plasma images at high spatial and temporal resolution were obtained by fast visible imaging with a wide angle video camera. The data gathered by different diagnostics was acquired using PXI and in-house developed data acquisition systems. After the data was transferred to server, it was available on the IPR intranet and analyzed using MATLAB, MDSplus, and other analysis software. The TF, TR, and BV coils of ADITYA-U are powered by a computer-controlled convertor pulsed power supplies. To facilitate the smooth communication among systems lying in the tokamak hall and the power supplies, optical fiber based trigger transmitters and receivers system with a programmable delay setting have been installed in ADITYA-U. The system is successfully operated during Phase I.

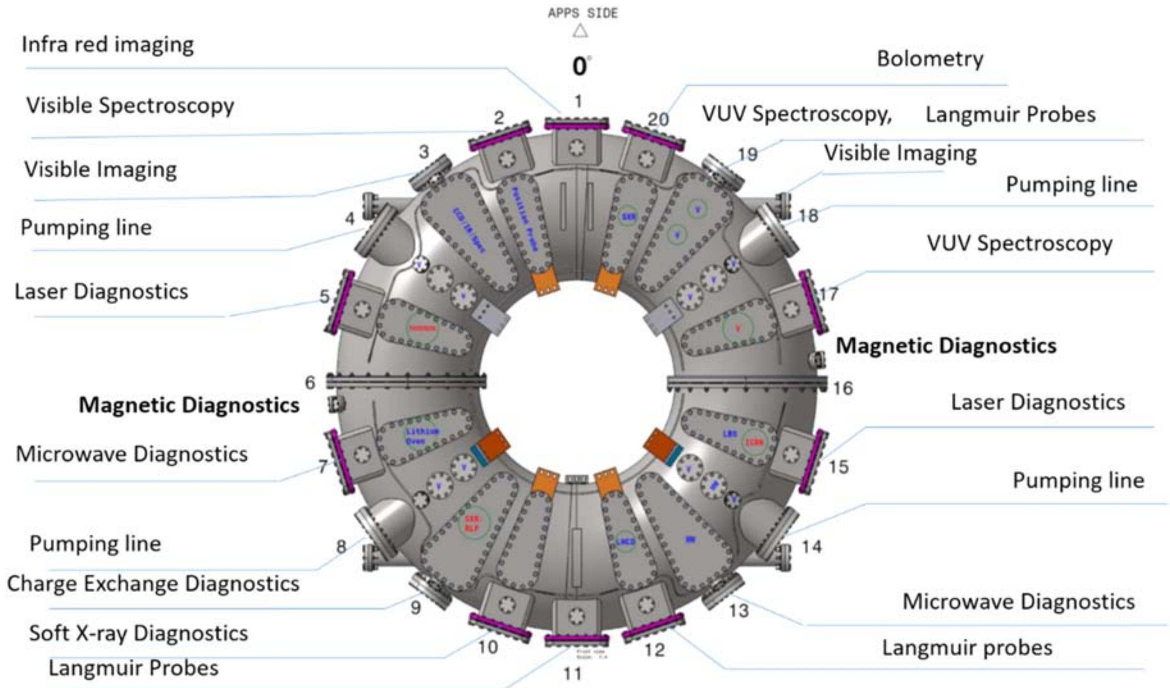

Figure 1. Port allocation to different diagnostics including pumping lines (top view).

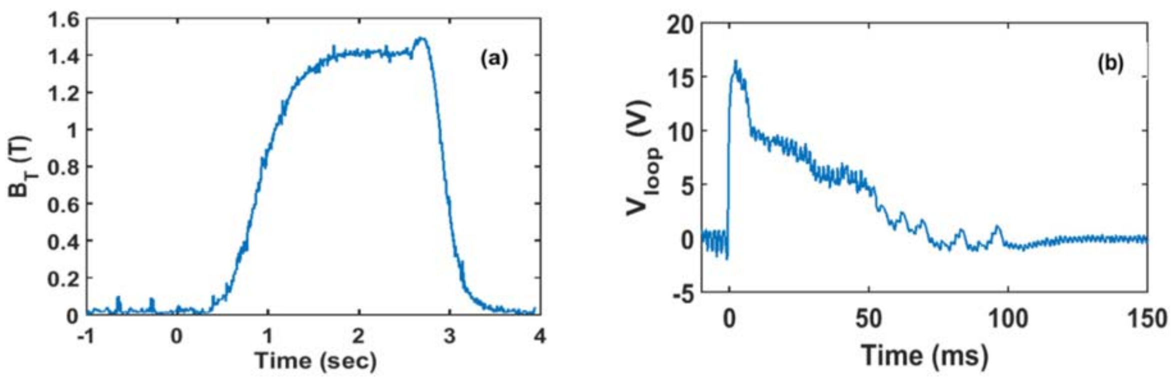

Figure 2. Measured (a) toroidal magnetic field (B_T) (T) and (b) loop voltage (V) during integrated power testing of the TF, TR, and BV coils of ADITYA-U.

3. Operational preparation before first plasma

After the commissioning of ADITYA-U, the TF, TR, and BV coils are successfully charged during integrated power testing. The TF coil assembly was tested at ~1.5 T, the Ohmic coil assembly was tested at ~12.5 kA producing a loop voltage of ~16 V. The vertical coil assembly was tested at ~3 kA. The TF coils displacement, fault current monitoring, loop voltage, and magnetic field measurements were carried out during current charging. The measured toroidal magnetic field and loop voltage at $R = 1$ m, $Z = 0$ is shown in figure 2. The movement of the outer vertical leg of the TF coils was recorded below 0.2 mm at full TF current. No fault current was observed during the test.

The loss of electrons due to an error in the magnetic field in the breakdown phase had to be minimized to get a successful discharge. Efforts were made to reduce the error in the magnetic field in ADITYA-U. All the magnetic field coils were accurately positioned with a precision tolerance of ±1 mm using a meteorological instrument during the commissioning of ADITY-U. The vertical asymmetry in the single turn correction coil (TR5) [21] for the Ohmic error field correction in ADITYA has been rectified in ADITYA-U. The total error in the magnetic field, B, and its vertical component, B_z, inside the vacuum vessel, due to Ohmic coils, have been measured at two different toroidal locations as a function of radius (R) and height (Z) by passing a 1 kA current through the Ohmic coil. The extrapolated values of B and B_z for 20 kA of Ohmic current are shown figures 3(a) and (b), respectively. The B_z component of the error field due to the Ohmic coils in ADITYA-U is observed to be an ~0.5 G /1 kA current in the Ohmic coils, which is half in magnitude as compared to ADITYA.

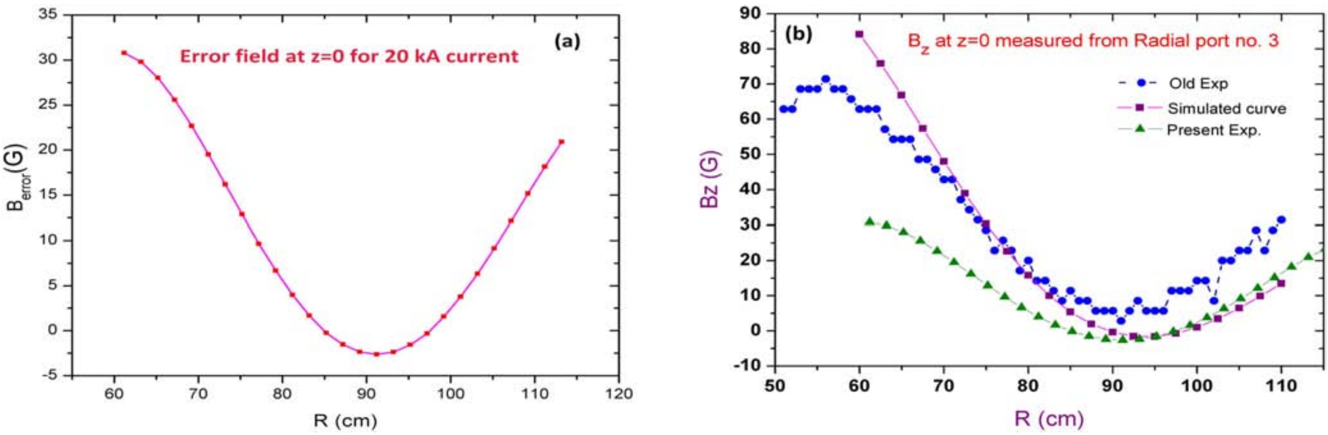

Figure 3. Measured error field (a) total (b) vertical component due to Ohmic coils in ADITYA-U.

Figure 4. (a) Safety and poloidal ring limiters. (b) Toroidal belt limiter.

Prior to the operation of ADITYA-U, the performance of the vacuum system had been tested successfully to achieve an ultra-high base vacuum. The pumping system was tested for high gas feed pressure in wall conditioning operations in the pressure range of 10^{-4}–10^{-2} Torr for long period of time (~12 h). After integrating pumping lines with the vacuum vessel, the leak testing of the entire vacuum system was carried out. Then the vessel was vented with nitrogen gas to install the Phase I in-vessel components. All the rectangular ports were opened and the PFC with graphite tile materials were installed inside the vacuum vessel. The plasma boundary was formed using an inboard toroidal ring limiter. Apart from the toroidal ring limiter there exists one outer limiter assembly installed at one particular toroidal location with a poloidal extent of 1/4 of the poloidal periphery of the vessel in the Phase I operation as shown in figure 4. In addition, one pair of the safety limiter, a poloidal ring of graphite tiles, was placed inside the vessel at toroidally symmetrical locations. Before the assembly of the PFC inside the vessel, all the graphite tiles were baked in a vacuum furnace for 24 h, at 1000 °C at a vacuum of $\sim 1.0 \times 10^{-5}$ mbar. The installation of other in-vessel components, viz., toroidal loops, diamagnetic rings, Rogowski coils etc was carried simultaneously. Later, GDC was carried out for several hours for several days.

4. Results and discussion

4.1. Discharge performance of ADITYA-U

After installation of the standard diagnostics in ADITYA-U along with their respective data acquisition systems, plasma operations were resumed in the upgraded machine in a graphite toroidal belt limiter configuration. The H_2 plasma is initiated and maintained by inductively induced voltage from the Ohmic transformer. The production and loss rates of electrons in a tokamak depend on few parameters, namely, the filled gas pressure, applied loop voltage, impurity influx, and error in the magnetic field. Hence, in ADITYA-U, the discharges are initiated using filament preionization. Gas breakdown has been obtained in each of ~700 discharges (Phase I) as shown in figure 5, without a single failure, in a fill-in pressure range of $(0.8\text{–}2.0) \times 10^{-4}$ Torr. The typical value of E/p is in the range of 225–625 V cm^{-1} Torr^{-1}, where E is the peak electric field and p is the H_2 filling pressure at the time of breakdown. The values of the intensity of H_α shown in figure 5 is only indicative of the observance of gas breakdown and the variation in the intensity is due to many factors such as fill pressure, line-of-sight, PMT voltages, and electronic gains etc.

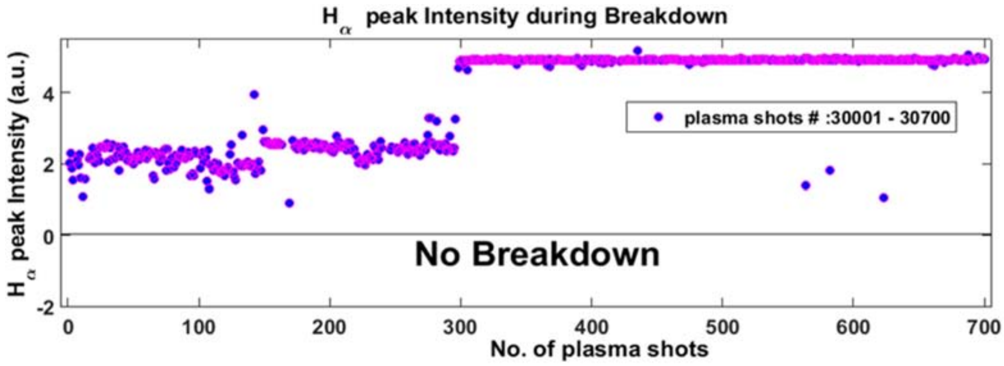

Figure 5. H_α peak intensity versus shot numbers for ADITYA-U Phase I operation.

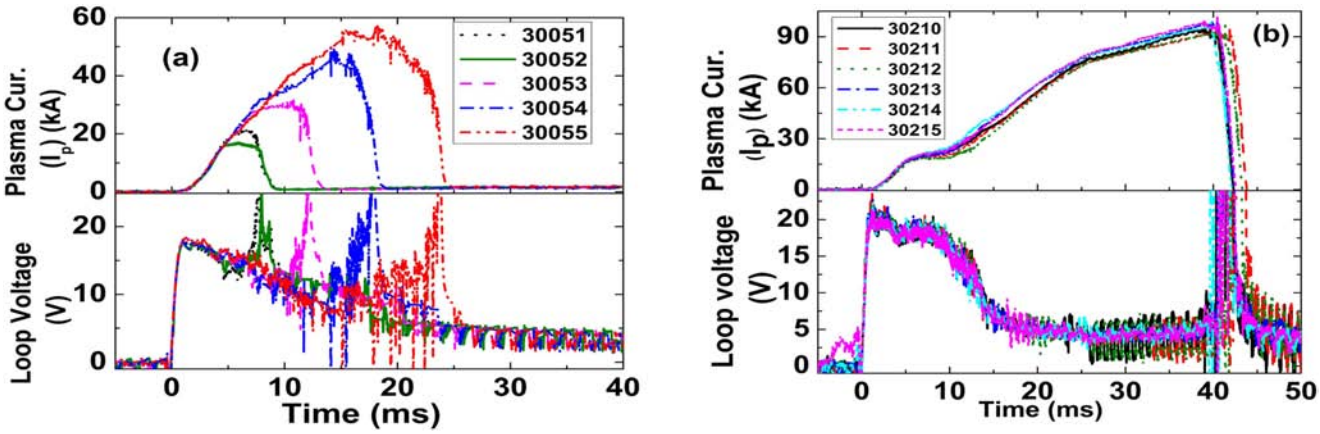

Figure 6. Time evolution of plasma current and loop voltage in ADITYA-U discharges. (a) Insufficient burn-through and (b) sudden disruption during current ramp-up.

The wall conditioning of the vacuum vessel is of great importance to achieve successful discharges, as the influx of hydrogen recycling and other low Z impurities (predominately carbon and oxygen) from the wall degrade the plasma confinement by increasing the Z_{eff} and even disrupt the discharges at the impurity burn-through phase [22]. At low temperatures (<100 eV), the impurities are not fully ionized. Neutral and partially ionized impurity ions radiate significantly, which could result in the loss of a significant part of the (Ohmic) heating power. Similar behavior has been observed in initial discharges of ADITYA-U. The time evolution of the plasma current and loop voltage of typical initial ADITYA-U discharges failing to evolve properly due to insufficient burn-through of H_α, OI, CIII impurities is shown in figure 6(a). The hydrogen GDC lasts for a long period of time ($\sim$12 h) and fast capacitor discharge pulses in the ECR plasma background have been performed routinely before plasma operation in ADITYA-U. Later, it was observed that the discharges achieved burn-through beyond 20 ms, and was suddenly disrupted at peak plasma current as shown in figure 6(b) due to MHD activities followed by an intensive spike in impurity line radiation.

As far as the in-vessel components are concerned, the major modification in ADITYA-U is the new toroidal belt limiter at the high field side, instead of the single poloidal ring limiter [23] in ADITYA at one toroidal location. This has increased the graphite surface area by 70% in ADITYA-U. Probably this is the reason why we need to supply higher loop voltages during the burn-through phase. In the present experiment, we adjusted all the available parameters: toroidal magnetic field, gas pressure, primary loop voltage, and its switching timings and equilibrium field. Optimum conditions for many of these were determined by properly adjusting the ramp rate of the plasma current. The discharge repeatability has been established in ADITYA-U as shown in figure 7. Only the positive converter was operational during these shots. So, the maximum Vs is available up to $\sim$80–90 ms. All the discharges were obtained in a typical gas fill pressure range of $\sim 1.6 \times 10^{-4}$ Torr, which is quite high as compared to the pressure range of ~ 0.8–1.0×10^{-4} Torr of ADITYA [21]. This has resulted in significant control of the runaway generation during the start-up phase.

The available Vs has been increased to 0.6 Vs by adding a negative converter, with 7 kA of current (0.2 Vs), to the positive converter having 12.5 kA of current (0.4 Vs) in order to increase the discharge duration. The positive and negative converters are coupled using a thyristor based dual polarity converter with a circulating rectifier for the smooth transition from positive to negative converters [24]. This will provide a constant flat-top loop voltage of $\sim$2 V during the negative

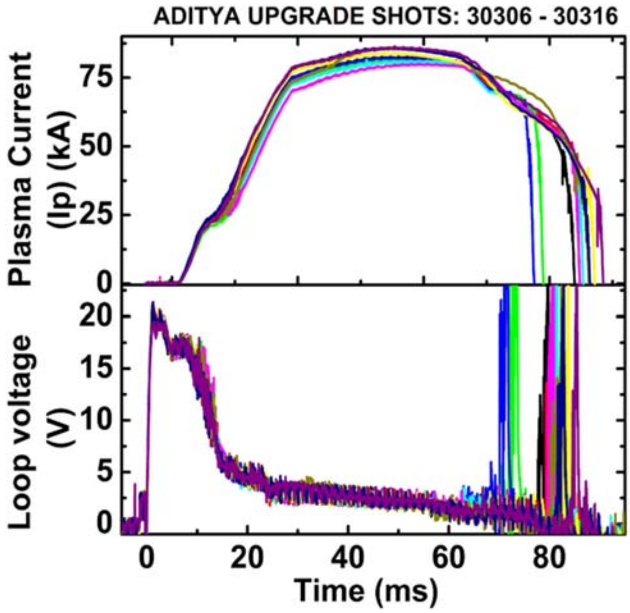

Figure 7. Time evolution of plasma current and loop voltage in repeated discharges (Shot #30306–30316) of ADITYA-U.

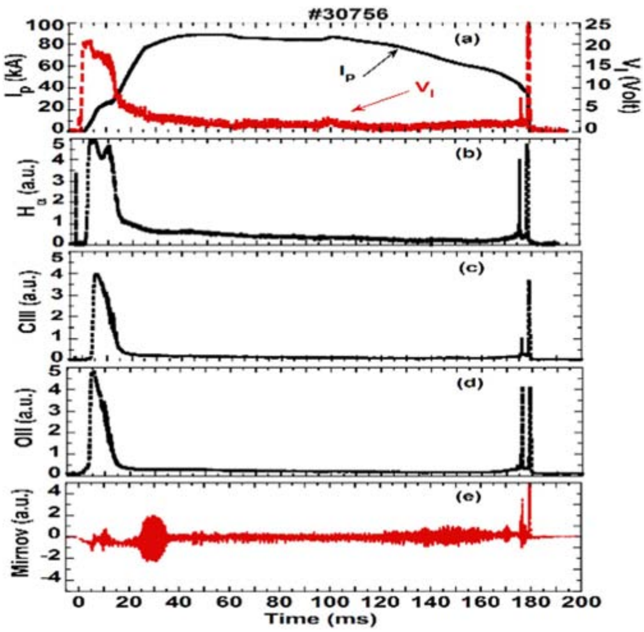

Figure 8. Time evolution of ADITYA-U shot #30756. (a) Plasma current, loop voltage, (b) H_α, (c) CIII intensity, (d) OII intensity, and (e) $\dot{B}_\theta$.

converter phase for above ~180 ms. The time evolution of a typical ADITYA-U discharge (#36756) with pulse length enhancement is shown in figure 8. Prior to the negative converter operation, extensive wall conditioning techniques were implemented in ADITYA-U. Previously, in the ADITYA tokamak it was observed that the gas mixture of hydrogen and inert gas had been used for better removal of carbon and oxygen impurity content and obtained low hydrogen retention in the vacuum vessel surface [25]. A similar technique has been implemented in ADITYA-U with

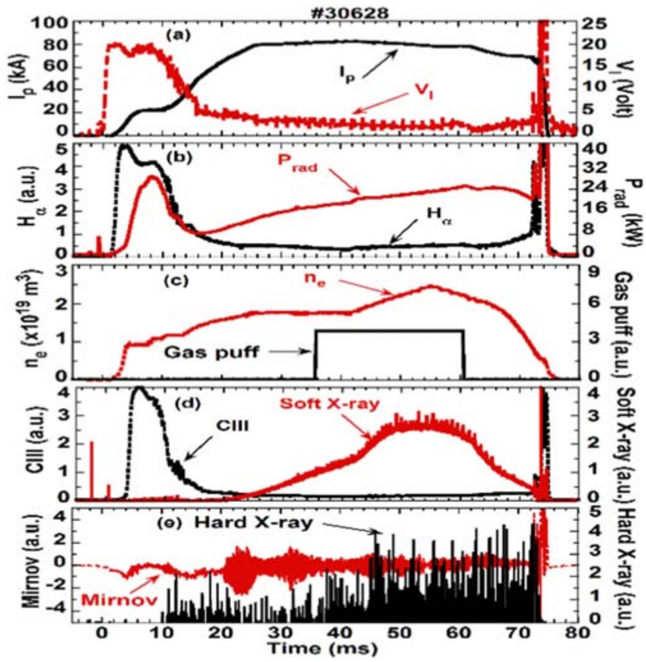

Figure 9. Time evolution of ADITYA-U shot #30628. (a) Plasma current, loop voltage, (b) H_α intensity, total radiated power, (c) electron density, gas pulse, (d) CIII intensity, SXR intensity, (e) $\dot{B}_\theta$ and HXR intensity.

an Ar:H_2 gas mixture of 50:50 and a He:H_2 gas mixture of 50:50, to reduce C and O impurities and hydrogen recycling. Both gases were fed from different toroidal locations into the torus through individual feed lines.

The partial pressure of various mass species like H_2, O_2, N_2, CO, CH_4, CO_2, and H_2O etc were monitored through a QMA. The partial pressure of various mass species, viz., H_2O (M #18), CO/N_2 (M #28), CO_2 (M #44), O_2 (M #32), and H_2 (M #2) reduced by a factor of 10 with gas mixture assisted GDC. The observed reduction in the loop voltage during flat-top was ≈2 V. The maximum discharge duration of ~180 ms was obtained during the Phase I operation of ADITYA-U. The drop in plasma current during the auxiliary converter phase (60–95 ms) (figure 8(a)) was due to slightly lesser loop voltage (~1.6 V) available during that phase. The disruptions during the plasma current flat-top due to sudden growth of MHD modes (figure 8(e)) are steered through by properly adjusting the ramp rate of the plasma current and the equilibrium (vertical) magnetic field. It can be seen from figures 6(b), 7(a), and 8(a) and (e) that the plasma current ramp rate between 25 and 40 ms is higher in the disrupted discharges, whereas when the ramp rate is reduced in this time zone, the MHD did not grow and plasma did not disrupt.

4.2. Density enhancement

In several shots in ADITYA, puffing of the fuel gas had remained a standard tool for increasing the plasma density [26] along with molecular beam injection [27]. In ADITYA-U, the single broad hydrogen gas puff is introduced at the plasma current flat-top as shown in figure 9(c) to increase the plasma density. The calibration experiment yielded a pressure

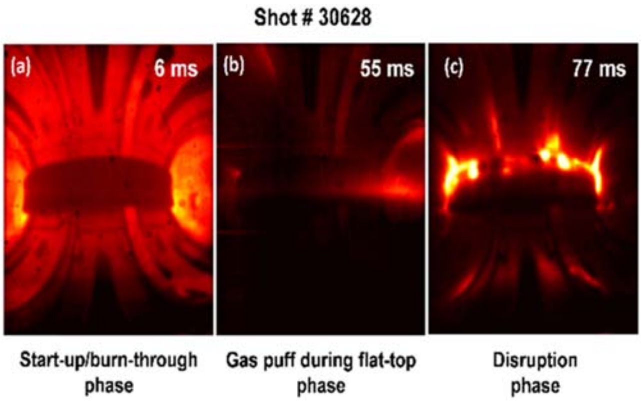

Figure 10. Snapshots of shot #30628. (a) Start-up/burn-through phase at 6 ms, (b) gas puff during flat-top at 55 ms, and (c) disruption phase at 77 ms.

increase of 3×10^{-5} Torr in the vessel during the gas puff, which is equivalent to an addition of $\approx 10^{18}$ molecules of hydrogen gas. The amount of injected gas is controlled in such a way that no significant change occurs in the plasma current and its equilibrium position. The pulse width timing and voltage level, time (T) for the gas puff to start has been pre-programmed with a programmable pulse generator. Figure 9 shows the temporal evolution of the ADITYA-U shot #30628 for the parameters (a) plasma current, loop voltage, (b) H_α emission, total radiated power (P_{rad}), (c) chord average electron density (n_e), gas puff, (d) CIII impurity line radiation, SXRs and (e) HXRs, and Mirnov oscillation. The typical discharge is obtained at toroidal field (B_ϕ) $\sim$1 T and hydrogen prefilled pressure of $\sim 1.6 \times 10^{-4}$ Torr, which is equivalent to $\approx 9.3 \times 10^{18}$ molecules of H_2 gas introduced into the vessel. Figure 9(c) shows the chord average electron density raised up to the maximum of 2.5×10^{19} m^{-3} and the control MHD activities (figure 9(e)) as well as the HXRs (figure 9(e)).

The increase in the SXRs during gas puff as shown in figure 9(d) is a combination of density, temperature, and Z_{eff} and shows an improvement in plasma confinement. A fast visible imaging video camera for 2D tangential viewing was installed on ADITYA-U, and captured a wide angle panoramic view of the tokamak from the radial port. The entire poloidal cross section including the limiter is within the field of view of the camera. Data was acquired at 14 kHz, and the consecutive frames were 71 μs apart. Excellent images of plasma evolution at high spatial and temporal resolution were obtained during start-up/burn-through, gas puff at flat-top, and during disruption phase, and are shown in figure 10.

4.3. HXR (runaway) suppression in high-density discharges

Apart from the density enhancement, we also studied the runaway suppression by enhancing the line average electron density of the discharges. Suppression of runaway electrons by increasing the density including strong helium gas puff has been studied in the TEXTOR, ASDEX, and JET tokamaks [28]. The runaway electrons in ADITYA-U are detected by measuring the limiter generated HXRs using a NAI (Tl) scintillation detector placed in front of the limiter to measure the HXR emission from the limiter. Intensive bursts of HXR emission with energies reaching up to $\sim$5 MeV have been observed in the plasma current flat-top region in discharges with densities $\leqslant 1.2 \times 10^{19}$ m^{-3}. However, in the high-density discharges, where the density is maintained at $\geqslant 1.5 \times 10^{19}$ m^{-3} in the plasma current flat-top mainly by using the multiple periodic gas puffs, the runaway generation ceases. The time evolution of two representative low (shot #30572, blue) and high (shot #30595, red) density, ADITYA-U discharges are shown in figure 11. It can be clearly seen from the figure that in the high-density discharge, the HXR intensity is significantly less compared to the low density discharge. The production and loss rate of runaway electrons depends exponentially on the parameter $\xi = E/E_{crit}$. Where E is the electric field and E_{crit} is the field for which a thermal electron would runaway. $E_{crit} \sim Z_{eff}\, n_e/T_e$. If Z_{eff} and T_e do not change much, then an increase in electron density with gas puff increases the critical electric field. This helps in restricting the thermal electrons from going into the runaway regime.

This has resulted in a significant reduction of HXR flux (figure 11(e)) in the flat-top as well as the runaway current contribution in the main plasma current (figure 11(a)) is also reduced with gas puff.

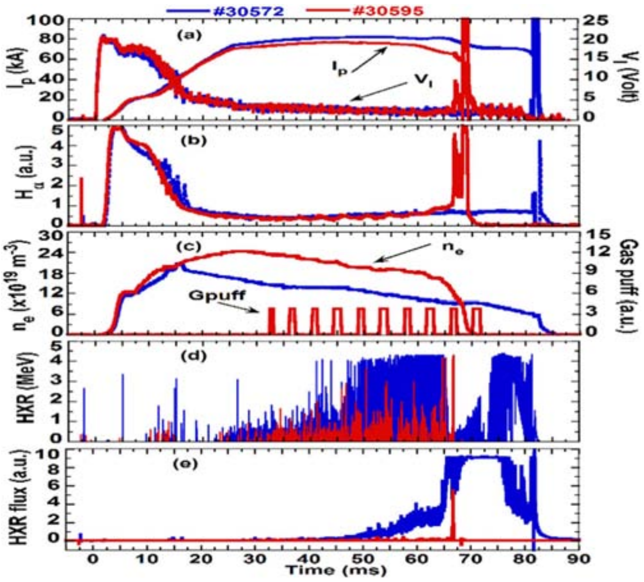

Figure 11. Time evolution of discharges (shot #30595, red) and (shot #30572, blue). (a) Plasma current, loop voltage, (b) H_α line emission, (c) electron density, H_2 gas puffs, (d) HXR intensity and (e) HXR flux.

5. Summary

The ADITYA tokamak with a limiter configuration has been upgraded to the ADITYA-U tokamak with an open divertor configuration. After successful commissioning and integrated power testing of ADITYA-U, the installation of various subsystems viz., pumping lines, PFC components, standard tokamak diagnostics, and their respective data acquisition systems was pursued to obtain the first plasma discharge in ADITYA-U on December 1, 2016. Filament preionization assisted purely Ohmic discharges with circular plasma were operated during Phase I operation. Hydrogen gas breakdown has been obtained in each of the ~700 discharges without a single failure in a fill-in pressure range of ~(0.8–2.0) × 10^{-4} Torr and a typical value of E/p ratio in the range of ~225–625 V cm^{-1} $Torr^{-1}$. The discharge failure in the burn-through phase has been mitigated with extensive wall conditioning along with proper tuning of the operating parameters. In the first phase of operations, repeatable plasma discharges of plasma current of ~80–95 kA with a duration of 80–100 ms with maximum $B_\phi \sim 1$ T, chord-averaged electron density ~2.5 × 10^{19} m^{-3} and temperature (estimated) >150 eV has been achieved. Later, the discharge duration was enhanced up to ~180 ms with the application of a negative converter power supply along with better wall conditioning being achieved by implementing the GDC with Ar:H_2 gas mixture as well as the He:H_2 gas mixture. The disruptions during the plasma current flat-top due to the sudden growth of MHD modes are steered through by properly adjusting the ramp rate of the plasma current. The generation of runaway electrons is controlled using high fill-in pressure during the breakdown phase and by multiple hydrogen gas puffings during the plasma current flat-top.

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