Equilibrium Magnetic Field Requirements during Plasma Initiation and Current Ramp-up Phase in ADITYA/ADITYA-U Tokamak Discharges*)

Rakesh L. TANNA[1,2], Joydeep GHOSH[1,3], Chetnarayan GUPTA[1], Balakrishnan V. NAIR[1], Shivam GUPTA[1], Moti N. MAKWANA[1], Kunal SHAH[1], Supriya NAIR[1], Rohit KUMAR[1], Suman AICH[1], Kumarpalsinh A. JADEJA[1,5], Kaushal M. PATEL[1], Tanmay MACWAN[1,3], Kaushlender SINGH[1,3], Suman DOLUI[1,3], Ankit KUMAR[1,3], Chetna CHAUHAN[4], Rajendra P. BHATTACHARYAY[1], Prabal K. CHATTOPADHYAY[1,3], Malay Bikas CHOWDHURI[1], Ranjana MANCHANDA[1], Yogesh Chandra SAXENA[1] and the ADITYA-U Team[1]

[1] *Institute for Plasma Research, Nr. Indira Bridge, Bhat, Ghandhinagar, Pin. 382 428, India*
[2] *Institute of Science, Nirma University, Ahmedabad 382481, Gujarat, India*
[3] *Homi Bhabha National Institute (HBNI), Mumbai 400085, India*
[4] *Institute of Technology, Nirma University, Ahmedabad 382 481, Gujarat, India*
[5] *Department of Physics, Saurashtra University, Rajkot, Gujarat, India*

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Plasma equilibrium in ADITYA/ADITYA-U is provided by two pairs of vertical field coils (BV1 & BV2) placed outside the vessel. A peak loop voltage of ~20 V is required for successful breakdown and start-up in ADITYA, which leads to a higher I_P ramp-rate ~6 - 8 MA/Sec during the first ~7 ms of discharge. To hold the plasma column in equilibrium, the vertical field should also be ramped-up at the same rate. Series connections of vertical field (BV) coils do not provide the required ramp rate due to the high L/R time-constant of the coils and 12 pulse converter firing. Therefore, additional arrangements are made to achieve it. The addition of a pre-charged capacitor of 500 μF/3 kV with VF converter based power supply allows successful start-up but causes concern about a slight dip that is observed in the plasma current. To obtain proper stabilization, two techniques are used. One is the paralleling of BV coils, and second is using the combination of another capacitor bank of 19.5 mF/1.2 kV and IGBT based power supply have improved the plasma performance and raised the $I_P \sim 150$ kA with $dI_P/dt \sim 3.0$ - 3.5 MA/s in ADITYA. In this paper, the effect of the equilibrium field in accordance with plasma performance is discussed in detail.

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1. Introduction

In pursuit of controlled thermo-nuclear fusion research, the first indigenously built ohmically heated, air-core tokamak, ADITYA ($R_0 = 0.75$ m, $a = 0.25$ m) had been operated with a single poloidal ring limiter (mostly graphite) for more than 2 decades [1]. Later, it was upgraded to the ADITYA Upgrade (ADITYA-U) tokamak, which was designed to perform shaped plasmas operations in an open divertor configuration with the addition of three new sets of divertor coils. The first Plasmas in ADITYA-U were established in December-2016 with the inclusion of a new graphite toroidal belt limiter as the primary plasma-facing component [2]. The achieved plasma parameters in ADITYA-U are plasma current (I_P) ~ 150 - 200 kA, maximum $I_P(T) \sim 400$ ms, chord averaged $n_e \sim 1.5$ - 5×10^{19} m^{-3} and max. $T_{e0} \sim 300$ - 500 eV, with max. Toroidal field operated up to 1.5 T (100% of the design value) and minimum base vacuum ~ 5×10^{-9} Torr [3, 4].

In a tokamak, toroidal plasma, considered as a current carrying ring, tends to expand under the influence of its own Hoop Force, as the field produced by the plasma current is stronger on the inboard side than on the outboard side. For plasma equilibrium, an equal and opposite force must be applied to prevent the plasma current ring from expanding. ADITYA tokamak had two pairs of vertical field coils (namely BV1 & BV2) placed outside the top and bottom of the vacuum vessel equidistant from the horizontal mid-plane on the high and low toroidal magnetic field sides, as shown in Fig. 1, along with other coil systems.

author's e-mail: rakesh@ipr.res.in

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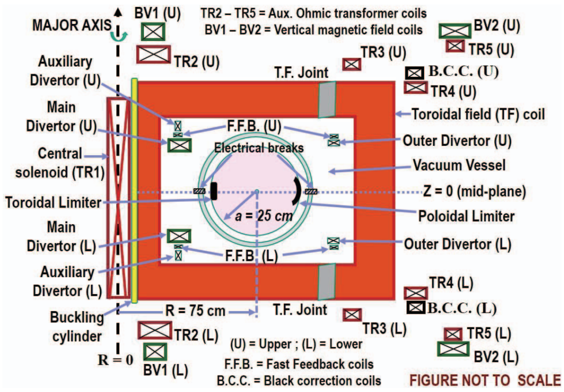

Fig. 1 A schematic of vertical cross section of ADITYA-U coils, vacuum vessel and other machine components.

Usually, when all four BV coils are connected in series to provide vertical field with the available VF power supply, a 12 pulse converter based system having 2250 V/12.5 kA, cannot support the higher I_P ramp-rate due to high L/R time constant of the coils. Hence to support the high ramp rate of the plasma current, first, a pre-charged capacitor of 500 μF/3 kV is added to VF coil to raise the current ramp-up in BV coils during the initial phase along with the pre-programmed VF current of the converter power supply. The selection of 500 μF capacitance is chosen based on the required stored energy in the capacitor to charge the BV coils load to 500 A during the first 5 ms. The vertical magnetic field (B_V) of the order of ∼135 G is produced at plasma center (R_0 = 0.75 m) by charging the 1 kA of current in BV coils. Total energy required to charge the BV coil load is of the order of ∼2250 J ($E_{\text{coil}} = 1/2 * L * I^2$; L = 18 mH, I = 500 A). The Inductance (L) = 18 mH is the total inductance of BV coils load at the power supply end, which includes the BV coils inductance when connected in series and its busbar connections along with the inductance of the Anti-transformer ∼4.06 mH. The anti-transformer is used to nullify the mutual coupling between Ohmic and BV coils as discussed in Section 4. Further, to drive 500 A in 5 ms, i.e., 100 A/ms, a minimum of 1800 V is required ($V = -L * dI/dt$; L = 18 mH and dI/dt = 100 A/1 ms). Keeping the induced voltage from OT in mind, the Voltage ∼3000 V is considered. To fulfill the energy and voltage requirements of ∼2250 J and 3000 V respectively, a 500 μF capacitor is chosen ($E_{\text{cap}} = 1/2 * C * V^2$; here C = 500 μF, E_{cap} = 2250 J). In this case too, although the successful start-up of plasma current has been achieved, however, a dip in the plasma current (I_P) during start-up has always been observed in most of the ADITYA discharges. The effect of various configurations of equilibrium field applications in accordance with the circular plasmas performance improvement in ADITYA/ADITYA-U tokamak using limiter configuration only will be discussed in this article.

2. Equilibrium Field Requirements

The equilibrium of the toroidal plasma current column is mainly provided by means of an externally applied vertical magnetic field (B_V) is given by the equation. . . . .

$$B_V = \frac{\mu_0 I_P}{4\pi R_0}\left[\ln(8R/a) + \beta_p + \frac{l_i}{2} - \frac{3}{2}\right]. \tag{1}$$

Here, for the ADITYA/ADITYA-U tokamak, R_0 = 0.75 m, a = 0.25 m, β_P = 0.84, l_i = 1.0, the required BV for plasma current (I_P) of ∼250 kA is of the order of 1000 Gauss. Therefore, 4 G of BV per 1 kA of plasma current is required to maintain the horizontal plasma position with circular plasma operation. With a purely vertical field, $B_V = B_Z$, the plasma is unstable relative to its displacement in the vertical direction. For stability of plasmas against motion in vertical and radial directions, there should be a radial component of the field and the vertical field should be curved. If the line of force of the confining field is slightly concave towards the major axis and $B_V = B_Z + B_R$, then any accidental displacement in the vertical direction is opposed by the restoring force $F_Z \sim I_P \times B_R$, and plasma position is stable with regard to up and down motion. The concavity of the vertical field line is written as the decay index given by equation . . . . .

$$n = -\left(\frac{R}{B_V}\right)\left(\frac{dB_V}{dR}\right). \tag{2}$$

It is linked to the curvature of BV and the vertical variation of its radial component. For stability against vertical displacement $n > 0$. Normally, BV coils are connected in series to provide a vertical field with Index (n), lies between ∼0.4 and 1.2 [5].

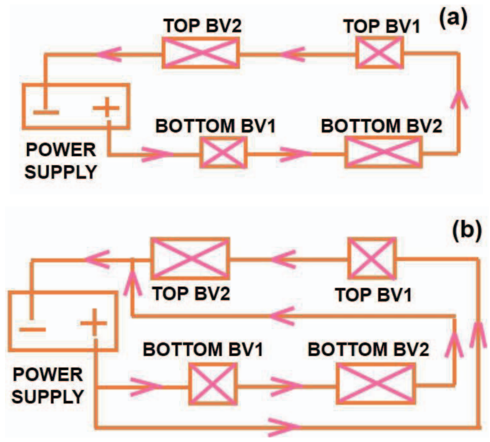

Fig. 2 Schematic diagram for BV coils (a) Series configuration and (b) Parallel configuration.

There are mainly two configurations of BV coils used in ADITYA and ADITYA-U, viz., series configuration of BV coils and parallel configuration of BV coils, as shown in Figs. 2 (a) and 2 (b) respectively. The inductance (L) and resistance (R) of BV coils are 11 mH and 60 mΩ, respectively, while BV coils are connected in series. Whereas the inductance (L) and resistance (R) of the upper BV coils are 5.6 mH and 30 mΩ, respectively, and for the lower BV

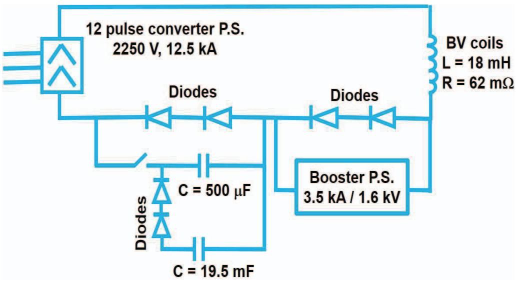

Fig. 3 A block diagram of VF converter power supply.

Table 1 VF power supply parameters versus plasma performance.

Parameters	Value	Remarks
Total inductance (L) / resistance (R) of BV coils in series	18 mH	The initial rise is slow due to the 12 pulse converter firing as well as the high L/R time constant of the BV coils in series.
	62 mΩ	
DC voltage / Peak current	2.25 kV / 12.5 kA	
Max. dI/dt by P.S.	60 – 80 A / ms	
Initially, a 500 μF capacitor was charged	3 kV	Supported I_P is *30 kA* in 5 ms. Later, observed a dip in the plasma current during start-up.
t/4	5 ms	
Current support by capacitor	350 Amps	
An external cap. bank of 19.5 mF is added in parallel with 500 μF	1200 V	Improved dip in the I_P during 5 to 12 ms. I_P rise-rate of 2.6 MA/s in the first 50 ms
t/4	22 ms	
External IGBT based Booster P.S. of 1600 V pre-charged regulated in series with the VF converter	1 kV – 1.4 kV is added in dI/dt of VF current	I_P of ~ 75 KA rises in 20 ms, 150 kA in 50 ms. I_P rise-rate of ~ 3 – 3.5 MA / S during ramp-up.

coils are 5.4 mH and 30 mΩ, respectively, while the BV coils are connected in a parallel configuration. The current direction in all BV coils is counter-clockwise as seen from the top. In the parallel configuration of BV coils, the busbar connections of BV coils are modified with a minimum change over from series to parallel configuration. The top and bottom sets of BV coils are connected in such a way that the overall machine symmetry remains the same.

A block diagram of the BV coil power supply, including a 12 pulse thyristor control rectifier based converter system and capacitor charging arrangement, is shown in Fig. 3. The VFPS parameters versus plasma performance are shown in Table 1. When BV coils are connected in series, the initial rise of BV current is slow (max. di/dt ~60 - 80 A/ms) due to the 12 pulse converter firing as well as the high L/R time constant of BV coils. Normally, ADITYA discharges are operated in the presence of weak filament pre-ionization. A peak loop voltage of ~20 V is required for successful breakdown and plasma start-up in ADITYA. This leads to a higher plasma current ramp-rate of 6 - 8 MA/Sec during the first ~7 ms of the discharge. To hold

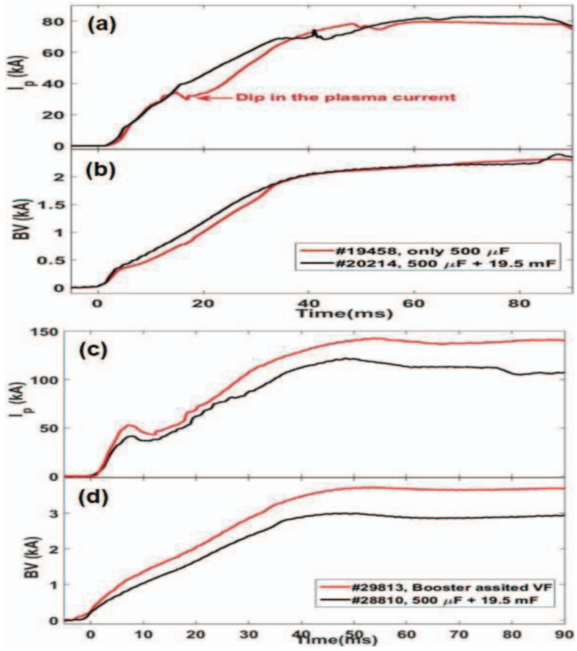

Fig. 4 Time traces of ADITYA shots (#19458, red) with only 500 μF, (#20214, black) with 500 μF+19.5 mF (a) plasma current (kA) and (b) BV current (kA), (c) and (d) Booster PS assisted IP (kA) and BV (kA) in series mode of BV coils.

the plasma column in equilibrium with this high ramp-rate of plasma current, the vertical magnetic field (VF) should also be ramped up at the same rate.

As mentioned in Section 1, the 500 μF/3 kV capacitor along with VF converters solves the I_P - B_V rise-rate matching problem during the initial current rise till ~5 ms. However, a dip in plasma current has always been observed after this initial 5 ms, again due to the I_P - B_V rise-rate mismatch. Hence, another capacitor bank of 19.5 mF/1.2 kV is added in parallel with 500 μF (shown in Fig. 3) to remove the dip in the plasma current during the impurity burn through phase, i.e., after ~5 ms into the discharge, as shown in Figs. 4 (a) and (b). Furthermore, while ramping up the plasma current beyond 100 kA during the first 30 ms, the 12 pulse VF converter power supply has a limited voltage (2 kV) and the higher L and R of BV coils in series configuration cannot be able to supply the programmed (required) vertical field during the first 30 ms. The selection of the 19.5 mF/1.2 kV capacitor is made in a similar fashion as the first capacitor, which is described in Section 1. Therefore, 19.5 mF/1.2 kV (t/4 = 22 ms) and 500 μF/3 kV (t/4 = 5 ms) help in supplying the programmed vertical field during the first 30 ms to ramp up the plasma current beyond 100 kA with an I_P ramp-rate of ~2.5 - 2.7 MA/s. Furthermore, in order to increase the plasma current at a rapid rate, the use of a booster power supply [6] in series with VF converters has been conceived in order to achieve better control over the B_V current rise-rate, which is quite limited with the capacitor banks

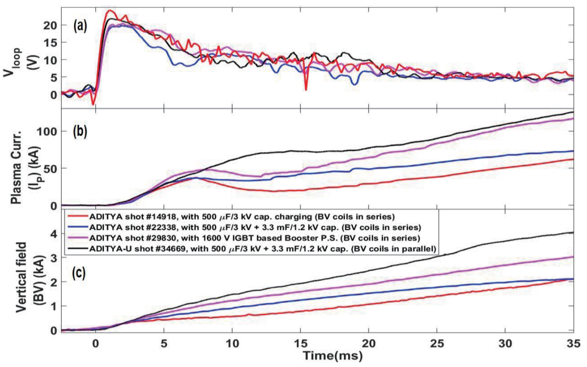

Fig. 5 Time evolution of ADITYA /ADITYA-U discharges parameters (a) loop voltage (V) (b) plasma current (kA) and (c) BV current (kA) shows the effect of various shapes of BV current in accordance with plasma performance.

mentioned above. Booster power supply is a two-stage IGBT based DC-to-DC buck converter (24 IGBTs are connected in parallel) rated at 800 volts and 3500 Amps, each making 1600 V operated at 10 kHz frequency (response time < 0.1 ms of IGBT). Its output voltage is regulated by the error signal. This error signal is generated from the given reference (BV current) and the actual BV current output. The booster power supply is connected in series with the thyristor based converter vertical field power supply (12.5 kA/2250 V). Hence, when operated along with the thyristor based converter vertical field power supply, it overdrives the BV (load) coils and hence the higher current rise rate in VF coils is obtained. The Booster power supply is bypassed after the plasma current ramp-up phase, i.e., after ~40 ms in ADITYA/ADITYA-U using bypassing diodes and the rest profile control by the VF converter power supply only. Because the higher *dI/dt* to the BV coils is added in current control mode, ramping up the plasma current (I_P) by 140 - 160 kA over 40 - 50 ms at a ramp-rate of 3.5 - 3.6 MA/s, as shown in Figs. 4 (c) and (d). In order to obtain I_P beyond 200 kA, an I_P ramp-rate of 4 - 5 MA/sec is required, which is not possible with the above series configuration of BV coils. Therefore, a parallel configuration of BV coils is implemented to achieve a faster response from the BV coils by reducing overall inductance and resistance. The time evolution of the ADITYA/ADITYA-U plasma parameters shown in Fig. 5 represents the effect of various shapes of BV current in accordance with the plasma performance. The highest ramp-rate of I_P and B_V current is observed in Fig. 5 (black curve) with a parallel configuration of BV coils. The top and bottom sets of BV coils should carry equal current in order to achieve a successful breakdown. Individual current sensors for top and bottom sets of BV coils are installed for individual sets of current monitoring.

3. Interpretation

A faster rise of BV current is achieved in the parallel configuration, even if the L/R time constant is similar for both series and parallel configurations of BV coils. For series configuration of BV coils (Fig. 6 (a)), V is the total voltage of the power supply, LdI_S/dt is self-induced voltage across the inductor, and I_SR is voltage drop across the resistance, then voltage V can be given as $V = I_SR + LdI_S/dt$; therefore, $dI_S/dt = V/L - I_S^* (R/L)$. Consider, at time t = 0, $I_S = 0$, therefore, $(dI_S/dt)_{t=0} = V/L$. When $I_S = I_{0S}$, $dI_S/dt = 0$, therefore, $I_{0S} = V/R$. Current I_S, at any time t can be written as

$$I_S = I_{0S}(1 - e^{-Rt/L}) = \frac{V}{R}(1 - e^{-Rt/L}). \quad (3)$$

Where $L = L_{coil} + L_{anti\text{-}transformer}$ and $R = R_{coil} + R_{anti\text{-}transformer}$. For series configuration of BV coils, the $L_{anti\text{-}transformer} \sim 4.45$ mH and $R_{anti\text{-}transformer} \sim 11$ mΩ for 100% coupling in the anti-transformer.

For the parallel mode of BV coils (Fig. 6 (b)), V is again the total voltage of the power supply, $(L/2)^*dI_P/dt$ is the self-induced voltage across the inductor, and $I_P*(R/2)$ is the voltage drop across the resistance, then voltage V can be given as $V = I_p*(R/2) + (L/2)^*dI_p/dt$, $dI_p/dt = 2V/L - I_p^*(R/L)$. Consider, at time t = 0, current $I_p = 0$, $(dI_p/dt)_{t=0} = 2V/L$. When $I_p = I_{0p}$, $dI_p/dt = 0$, therefore, $I_{0p} = 2V/R$. Current I_p, at any time t can be written as

$$I_P = I_{0P}(1 - e^{-(R/2)\times t/(L/2)}) = \frac{2V}{R}(1 - e^{-Rt/L}). \quad (4)$$

Where $L = L_{coil} + L_{anti\text{-}transformer}$ and $R = R_{coil} + R_{anti\text{-}transformer}$. For parallel configuration of BV coils, the $L_{anti\text{-}transformer} \sim 3.11$ mH and $R_{anti\text{-}transformer} \sim 7.7$ mΩ for 70% coupling in the anti-transformer.

The charging current profile's time evolution in series and parallel configurations are shown in Figs. 6 (a) and 6 (b). They show that for similar L/R time constant, the current rise rate is almost double for parallel configurations.

4. Results and Discussions

The electrical loads of the tokamak are the TF, Ohmic, and BV coils, which are subjected to pulsed operation. The geometry of Ohmic and BV coils is symmetric around the mid-plane. The close proximity of the Ohmic and BV coils

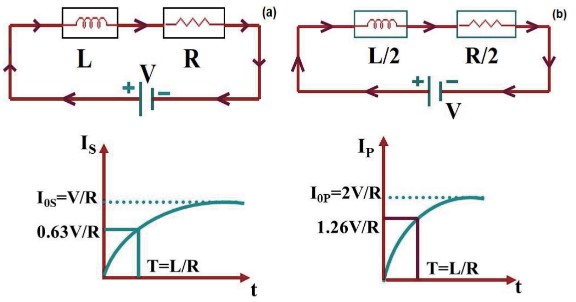

Fig. 6 L-R circuits and charging current profile for (a) Series and (b) Parallel configuration of BV coils.

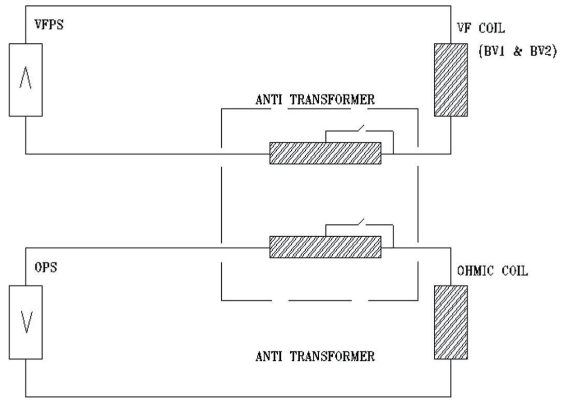

Fig. 7 A schematic diagram for anti-transformer in ADITYA.

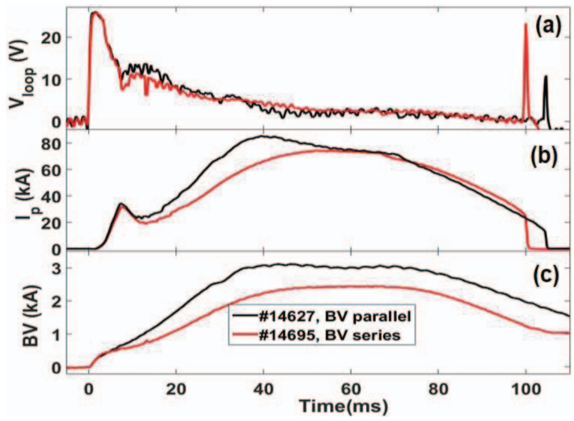

Fig. 8 Time evolution of ADITYA discharges parameters (a) loop voltage (V) (b) plasma current (kA) and (c) BV current (kA) for series and parallel mode of BV coils.

leads to high mutual inductance between them. The measured value is 3.5 mH, when BV coils are connected in series configuration. Whereas, the mutual inductance between Ohmic (TR coils) and BV coils is ~ 1.8 mH, when the BV coils are connected in parallel configuration. To avoid the induced voltages in the BV coils due to the fast variations of the Ohmic current during the breakdown and current ramp-up phase, an anti-transformer is connected in between the BV and Ohmic coils as shown in Fig. 7. The anti-transformer reduces the induced voltage in the BV coil due to fast current variation in the Ohmic coil and hence reduces the voltage requirement of the BV coil power supply during the initial breakdown and plasma current ramp-up phase. The anti-transformer has multiple tapping: one with 100% coupling is having an inter-winding mutual inductance (M) ~4.06 mH, whereas another tapping at 70% coupling is having an inter-winding mutual inductance of (M) ~2.85 mH. The third tapping with 30% coupling is having an inter-winding mutual inductance (M) ~1.21 mH. Hence, the proportion of rejection of the induced voltage in BV coil can be set to 100%, 70% and 30% in the anti-transformer using these different tapping. In case of series connections of BV coils, 100% of the anti-transformer coupling is used whereas when the BV coils are connected in the parallel mode, 70% of the anti-transformer coupling is used. Therefore, when the BV coils are connected in series (100% coupling in the anti-transformer is used in this case), the value of inter-winding mutual inductance of anti-transformer (M) ~4.06 mH is greater than the value of mutual inductance ~ 3.5 mH between the Ohmic & BV coils. When the BV coils are connected in parallel (70% coupling in the anti-transformer is used in this case), the inter-winding inductance of the anti-transformer (M) ~2.85 mH is greater than the mutual inductance ~1.8 mH between Ohmic & BV coils. Hence, proper compensation of induced voltages in BV coils are obtained for both of the series and parallel configurations.

Proper tuning of operating parameters is made in the BV current reference waveform as well as in the loop voltage shape to get a successful plasma discharge in the parallel mode of BV coil operation. Previously, in ADITYA, a faster BV and I_P rise rate was observed with the BV parallel mode. But, plasma current flattop could not be obtained because of the lower loop voltage available during that phase. ADITYA discharges are plotted in Fig. 8, which shows the time evolution of loop voltage, plasma current, and vertical field for series and parallel configurations of BV coils. Although, higher loop voltage is being utilized during the plasma current ramp-up phase with a parallel configuration as compared to a series configuration of BV coils. Following that, plasma current could not remain flat and gradually decreased, as shown in Fig. 8. It might be because the loop voltage available during that time may not be sufficient to drive that much plasma current. Later, as shown in Fig. 9 (e), real-time horizontal plasma position control [7] is implemented in ADITYA-U using a dual polarity fast feedback power supply and a field-programmable gate array-based (PID) controller. Extensive wall conditioning with lithium coating, along with proper tuning of loop voltage and I_P references, aids in maintaining the I_P flattop with a higher $I_P > 150$ kA as shown in Fig. 9 (b). Rise in Soft X-rays (Fig. 9 (d)) correlates with improvement in density, temperature and confinement. Furthermore, discharge consistency improvement (repeated discharges) beyond 150 kA of I_P has been obtained at toroidal field (B_Φ) ~ 1.28 T and observed loop voltage $\leq$ 2 V during I_P flattop in consecutive discharges of ADITYA-U with parallel mode of BV coils as shown in Fig. 10. The temporal evolution of discharges parameters shown in Fig. 10, attain almost similar plasma parameters in terms of mainly the plasma current and total duration of the plasma. Later, plasma pulse length enhancement (> 350 ms), as shown in Fig. 11 is achieved in ADITYA-U for the first time with the parallel mode of BV coils! The Volt-sec has been increased to 0.9 Vs (75% of the total available Vs) by adding a negative converter (0.47 Vs), to the positive converter (0.43 Vs) to increase the discharge duration. The Ohmic Transformer Power Supply (OTPS),

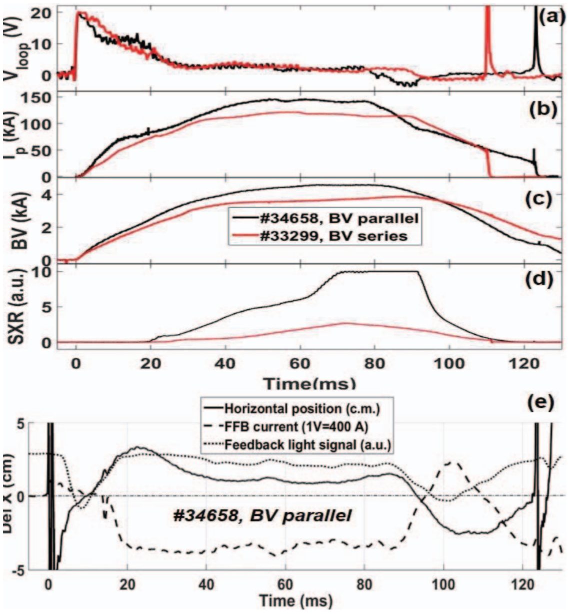

Fig. 9 Time evolution of ADITYA-U discharges parameters (a) loop voltage (V) (b) plasma current (kA) (c) BV current (kA) (d) Soft X-rays (a.u.) for series and parallel configurations of BV coils and (e) real-time horizontal position control for shot #34658.

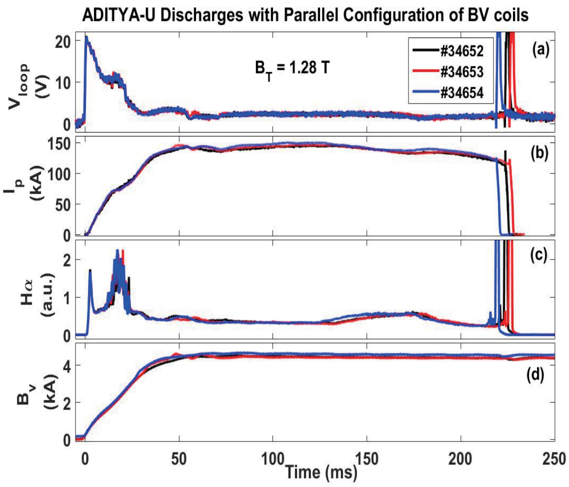

Fig. 10 Time evolution of ADITYA-U discharges parameters (a) loop voltage (V) (b) plasma current (kA) (c) H_α line emission (a.u.) and (d) BV current (kA) shows discharges repeatability with parallel mode of BV coils.

for loop voltage generation in ADITYA, is a four quadrant power supply consisting of three 12-pulse converters, a positive converter, a negative converter and an auxiliary (circulating) converter. The OTPS works in a dual converter configuration where positive and negative converters are connected back to back and the third converter is circulating converter connected in parallel. The circulating converter facilitates the smooth switching from positive to the negative converter. Almost ≥ 90% of the available flux has been utilized in the discharges shown in Fig. 11. The total

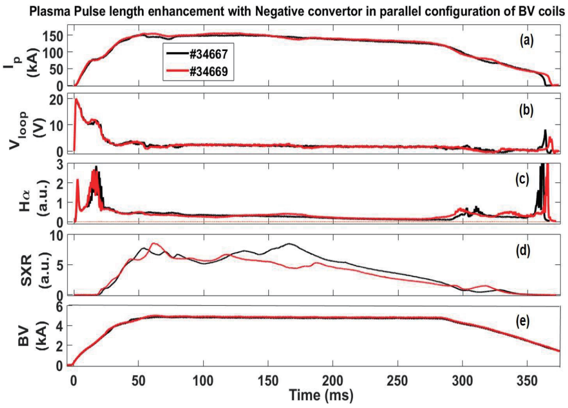

Fig. 11 Plasma pulse length enhancement with negative converter in BV parallel mode operation.

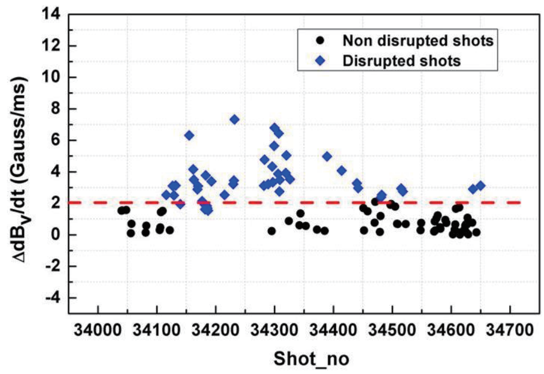

Fig. 12 The effect of BV current rise-rate on plasma disruptions in ADITYA-U.

plasma inductance (external + internal) is ~1.5 μH [8]. The plasma resistance is ~15 - 20 μΩ with Zeff ~2.5 - 3.0 and electron temperature ~250 - 300 eV in these discharges.

Disruption prediction in the early stages of tokamak discharge is very much essential to take corrective measures for disruption avoidance or mitigation [9, 10]. The role of the BV current rise rate on plasma disruption has been studied in ADITYA-U. It is observed that during the I_P ramp-up phase (22 - 45 ms), the vertical magnetic field plays a crucial role in holding the plasma in equilibrium. Hundreds of disrupted and non-disrupted discharges of ADITYA-U are analyzed, as shown in Fig. 12, and a sharp cutoff of the BV current rise rate has been found to avoid plasma disruption. It can be seen from the figure that the equilibrium field rise-rate of above 2 gauss/ms (i.e., B_V current rise rate of ~0.015 kA/ms), most of the discharges are disrupted. Whereas the equilibrium field rise-rate below 2 gauss/ms, disruption does not occur, which is a very important observation for disruption prediction in ADITYA-U. The edge safety factor (q) of the discharge reported in Fig. 12 is in the range of ~3.5 - 4 and the plasma internal inductance (l_i) is ~0.5 [8].

5. Summary

The effect of series and parallel configurations of equilibrium field coil applications in accordance with the circular plasma performance improvement in ADITYA/ADITYA-U has been studied. The fastest plasma current rise as well as the highest BV current rise were achieved in the ramp up phase with the parallel configuration of BV coils in ADITYA and ADITYA-U. For the first time, with the parallel configuration of BV coils, consistent discharges with $I_P \sim 170\,\mathrm{kA}$, duration ($t$) $\sim 370\,\mathrm{ms}$, and flattop duration $> 200\,\mathrm{ms}$ have been obtained. Appropriate wall conditioning, real-time horizontal plasma position control, and proper tuning of operational parameters led to the significant enhancement in plasma performance in ADITYA-U. Furthermore, in ADITYA-U, the role of the BV current rise rate on plasma disruption has been studied. A sharp cutoff of the BV rise rate has been found to avoid plasma disruption.

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