Controlling the Rotation of Drift Tearing Modes by Biased Electrode in ADITYA-U Tokamak

Tanmay Macwan[1,2], Kaushlender Singh[1,2], Suman Dolui[1,2], Ankit Kumar[1,2], Harshita Raj[3], Pramila Gautam[1], Praveenlal Edappala[1], J Ghosh[1,2], R L Tanna[1,4], Rohit Kumar[1], K A Jadeja[1,5], K M Patel[1], Suman Aich[1], Sameer Kumar[1], D Raju[1,2], P K Chattopadhyay[1,2], A Sen[1,2], Y C Saxena[1,2], R Pal[6]

[1] *Institute for Plasma Research, Gandhinagar 382 428, India*
[2] *Homi Bhabha National Institute (HBNI) University, Mumbai 400 085, India*
[3] *EPFL, Route Cantonale, 1015, Lausanne, Switzerland*
[4] *Institute of Science, Nirma University, Ahmedabad 382 481, Gujarat, India*
[5] *Department of Physics, Saurashtra University, Rajkot, Gujarat, India*
[6] *Saha Institute for Nuclear Physics, Kolkata 700 064, India*

E-mail: tanmay.macwan@ipr.res.in

Abstract

The influence of background plasma poloidal rotation on the rotation frequency of the m/n = 2/1 drift tearing mode (DTM) has been studied in ADITYA-U tokamak. The poloidal rotation velocity of the background plasma in the ion diamagnetic direction is increased or decreased by inducing an outward or inward radial electric field respectively through a biased-electrode placed in the edge region of the plasma. The rotation frequency of the pre-existing drift tearing mode, rotating in the electron diamagnetic direction, concomitantly decreased or increased with the application of bias depending on its polarity. The positive-bias increases the background plasma rotation in the ion-diamagnetic direction from its pre-bias value, hence decreasing the DTM rotation frequency, whereas the negative bias reduces the plasma rotation velocity in the ion-diamagnetic direction, hence increasing the mode rotation. In addition to that a short gas puff introduced during positive and negative bias pulse, further reduces the mode frequency, however, with different amplitudes in different bias-polarities. These observations suggest that the background plasma rotation contributes significantly towards the rotation of DTMs and the rotation frequency of the MHD modes can be modified by varying the poloidal rotation of the background plasma and/or the diamagnetic drift frequency.

Keywords: MHD instability, Plasma Rotation, gas puff, ADITYA-U tokamak, drift tearing mode, electrode biasing

1. Introduction:

In tokamaks, formation of magnetic islands originating from resistive tearing modes (mode numbers m ≥ 2) that limit plasma confinement remain a huge cause of concern for achieving good performance of this device. Resistive tearing mode (TM), a relatively slowly growing macro-instability driven by the free energy associated with the current density profile, is quite well-known and has been thoroughly studied in the tokamak community worldwide [1]. It forms radially localized helical structures of finite radial width, known as “magnetic islands”, through the process of magnetic reconnection. These islands enhance the radial plasma transport significantly and are hence detrimental to good plasma confinement. When these islands grow sufficiently large with respect to the plasma minor radius, complete loss of energy and particle confinement of the plasma occurs, also known as a major disruption [2].

Simultaneous existence and overlapping of multiple islands also lead to disruptions [1]. Due to their capability of altering the overall magnetic field topology leading to confinement degradation, controlling the TM instabilities are of paramount importance.

One of the mechanisms which limits the uncontrolled growth of tearing modes is their coupling to drift modes, which has been investigated as the so-called ‘drift-tearing mode’ [3-5]. In presence of pressure gradients, the magnetic islands are rotated by the electron diamagnetic effect. The growth rate of the tearing mode is significantly reduced as the mode rotates in the diamagnetic direction. The diamagnetic drift frequency, ω^*, approximately determines the rotation frequency of the linear drift tearing (DT) mode [3]. However, in the nonlinear phase of the drift-tearing mode, the pressure gradient around magnetic islands is flattened, and the diamagnetic drift frequency is modified. In the non-linear regime, the DT mode rotation frequency depends on the plasma rotation [6]. The plasma flow or rotation provides another mechanism of controlling the TMs in tokamaks. The plasma flow/rotation is known to have considerable effect on magnetohydrodynamic (MHD) instabilities, mainly stabilizing the tearing modes [7-8]. The stabilizing effect of sheared plasma flow on tearing mode has been demonstrated in a number of past experimental studies, such as in DIII-D and JT-60U tokamaks, where m/n = 3/2 neoclassical tearing modes (NTM) are stabilized by flow-shear [9-11]. Reducing the plasma flow reduces the TM stability and facilitates the growth of pre-existing saturated islands [12]. Numerical simulation also predicts that larger plasma rotation speed leads to a smaller TM growth rate in a linear phase while it leads to a smaller saturated island in the nonlinear phase [13]. Hence controlling the plasma flow/rotation offers a suitable means of controlling the TMs in tokamaks.

In the presence of plasma rotation, the rotation velocity of the magnetic island formed due to drift-tearing modes becomes a complex combination of its phase velocity in the plasma frame and the background plasma rotation velocity [6]. The interplay between magnetic island rotation and background plasma rotation is not fully understood as perturbing one is known to influence the other [14]. It has been reported that cessation of the island rotation due to its interaction with the resistive wall, modifies the plasma rotation leading to the degradation of confinement [12, 15]. Thus, understanding the rotation of magnetic islands in rotating background plasma is crucial for an effective application of TM control techniques. In several experiments, the plasma rotation has been modified to study the effect of background plasma rotation on the rotation of DTMs. The control of plasma rotation in large sized tokamaks is relatively difficult and has to be carried out using Neutral Beam Injection (NBI) and Neoclassical Toroidal Viscosity (NTV) injection [16-19]. However, in small/medium size tokamaks, a biased electrode is often sufficient to induce a strong plasma rotation which can be used to study and control the MHD modes. Resonant magnetic perturbations (RMP) have also been shown to influence the plasma flow velocity, *e.g.* in STOR-M tokamak [20]. It has been experimentally demonstrated in several tokamaks worldwide that the edge electrode biasing significantly influences the resistive MHD instabilities, both favourably and unfavourably [21-27]. In ADITYA tokamak, gas-puff induced disruptions have been successfully mitigated through the stabilization of 2/1, 3/1 MHD modes by biasing an electrode placed inside the LCFS [21, 22]. Electrode biasing has also been used in the SINP-tokamak to suppress MHD instabilities [26]. In HT-7 tokamak, efficient suppression of MHD instability has been reported, which has been found to be dependent greatly on the current drawn during the biased voltage electrode [23].

There have also been some dedicated experiments to study and control the MHD mode rotation frequency using electrode biasing. In the HBT-EP tokamak, the n (toroidal mode number) = 1 mode is controlled in real time, to rotate at a desired frequency in one direction by providing appropriate voltage to the electrode placed inside the last-closed flux surface (LCFS) [25]. In

J-TEXT tokamak [24], toroidal plasma rotation in counter-plasma-current direction, has been suitably influenced by a biased electrode and stabilization and destabilization of m/n = 2/1 TM have been observed depending on the bias polarity. However, much larger variations in mode rotation frequency, f_{MHD}, have been observed in comparison to the toroidal rotation speed V_{φ}, indicating a major role played by changes in plasma poloidal rotation. They suggested measurements of poloidal rotation velocity to distinguish its effect on the mode rotation frequency.

The DT modes (m/n = 2/1) have in the past been thoroughly characterised in ADITYA and ADITYA-U tokamak discharges [28]. Raj et al [28], have shown that the rotation frequency of DT modes, f_{DTM}, in ADITYA-U, rotating with diamagnetic frequency in the electron diamagnetic direction, can be reduced by application of a gas-puff during the discharge. The experiments and simulations [28] have shown that the gas-puff modifies the radial profile of the plasma pressure in the edge region, causing the reduction in the diamagnetic drift frequency, which is responsible for the reduction in the rotation frequency of the DT modes. In this paper, we report a detailed study of the influence of poloidal plasma rotation on the rotation frequency of drift-tearing (DT) islands in ADITYA-U tokamak [28]. The poloidal plasma rotation is altered by biasing a tungsten electrode placed inside the LCFS of ADITYA-U hydrogen plasma discharges. A biased-electrode modifies the equilibrium electrostatic potential on a local flux surface on which it lies, resulting in a change in magnitude and profile of the pre-bias radial electric field, E_r, mainly in the edge plasma region of ADITYA-U. The modification in E_r leads to corresponding changes in poloidal, $E_r \times B_\phi$ and toroidal $E_r \times B_\theta$ rotation of the edge plasma. Our main findings are that the application of the bias voltage of different polarities to the electrode placed inside the LCFS during the plasma current flat-top in typical discharges of ADITYA-U, modify the rotation frequency of DT mode differently. A positive bias decreases the f_{DTM}, whereas a negative bias increases it. The positive and negative bias set-up a radially outward electric field of different magnitudes depending upon the pre-bias radial electric field, which with the magnetic field configurations in ADITYA-U, rotates the edge plasma poloidally in the ion diamagnetic direction with different velocities. The positive bias increases the existing pre-bias plasma poloidal rotation in the ion diamagnetic direction, opposing the pre-existing DT mode rotation in the electron diamagnetic direction, hence reducing the f_{DTM}. Whereas, the negative bias decreases the pre-bias edge plasma poloidal rotation velocity in the ion-diamagnetic direction, leading to an increase in the f_{DTM}. Interestingly, an application of a gas-puff during the positive-bias period, decreases the f_{DTM} further, i.e., on top of the decrement due to positive bias. Similarly, the increase in the f_{DTM} associated with negative bias appeared to be balanced by the reduction in f_{DTM} due to the application of a gas puff. Furthermore, the observations of significant variations in f_{DTM} even in the case of reduced shear in radial electric field, indicates the significance of poloidal plasma rotation velocity in controlling the DT mode rotation, f_{DTM}.

The paper is organized as follows. Section 2 presents the experimental set up, section 3 comprises of experimental results and discussion. The paper is summarised in section 4.

2. **Experimental Set-up:**

The experiments are carried out in circular (toroidal belt limiter and poloidal quarter-rings limiters) Ohmic discharges of ADITYA-U tokamak (R = 0.75 m, a = 0.25 m) [29, 30] having plasma parameters in the following ranges: Plasma current, $I_p \sim 80 - 100$ kA, toroidal magnetic field $B_T \sim 0.9 - 1.0$ T, chord averaged density, $\overline{n_e} \sim 1 - 3 \times 10^{19}\ m^{-3}$, and central electron temperature, $T_e \sim 250 - 300$ eV. The horizontal plasma position is controlled using a real-time feedback system [31]. The edge safety factor, q_{edge} lies in the range of ~ 3.2 – 4.0

for these discharges. The plasma parameters are measured using standard magnetic and spectroscopic diagnostics [32]. The chord-averaged density is measured by a microwave interferometer and the central electron temperature is estimated from soft X-ray emissions using the foil ratio technique [33]. To identify the MHD modes and their activities, the related poloidal magnetic fluctuations are measured by two sets of 16 poloidal Mirnov coils with uniform poloidal separation installed radially outside the scrape-off-layer (SOL) region at two opposite toroidal locations ($\varphi = 90^0$ and 270^0) [28]. Two arrays of Rake Langmuir probe (LP) were used to measure the edge plasma parameters (density, potential and temperature) and its fluctuations. The two LP arrays are installed on the top and bottom port of the vacuum vessel at one toroidal location, 126^0 away toroidally from the location of the biased electrode. Each array consists of seven equidistant cylindrical probes of *4 mm* diameter and *4 mm* length with an inter-probe separation of *8 mm*. All data are recorded at a sampling frequency of 100 kHz.

For introducing a radial electric field in the edge region of ADITYA-U tokamak, a cylindrical tungsten electrode with a diameter of *8 mm* and exposed length of *15 mm* is used. A slightly modified electrode holding assembly that had been used in previous biasing experiment in ADITYA [34], is used for inserting the electrode inside the LCFS. The electrode is held inside an alumina ceramic assembly, which can be radially translated inside the last closed flux surface (LCFS) on a shot-to-shot basis. Keeping in mind the temperature rise, ΔT, of the electrode due to its presence in plasma of $n_e \sim 5 \times 10^{18}\ m^{-3}$, $T_e \sim 50 – 70$ eV, for more than $\sim$ 200 ms, tungsten is chosen as electrode material. In the experiment reported in this paper, the electrode-tip position is kept fixed at *r = 22.5 cm*, which is *2.5 cm* inside the LCFS. The electrode can be biased up to *+/- 900 V* using a 30 *mF* capacitor based power supply. Usage of an Insulated Gate Bipolar Transistor (IGBT) as a switch facilitates a maximum voltage variation of ~ 20 kHz on the electrode. Thus, the electrode can be biased multiple times in a single discharge. The schematic of electrode bias set-up used for the reported experiments is shown in figure 1. The IGBT (Semikron make SKM 400GA 12E4) is turned on and off by a gate driver circuit (Semikron make driver SKYPER 32R) connected to a function generator (FG in figure 1a) for applying desired voltage pulses of different magnitude and duration, to the electrode. The voltage across the electrode (V_B) is measured by a passive attenuator (1:100), which represents the total applied voltage to the electrode. A Pearson current monitor measures the bias current drawn by the circuit through the plasma. Maximum power drawn by the electrode is less than $\sim$ 10 % of total input Ohmic power to the plasma. The voltage-current characteristic for the electrode during biasing, obtained on a shot-to-shot basis, is shown in figure 1b. The bias current drawn is dependent on the difference between the plasma potential at the electrode location and the applied voltage to the electrode. The plasma potential at the electrode location varies on shot to shot basis; however, it remains positive in the majority of the discharges analysed and presented in this paper. Furthermore, as the bias polarity and magnitude is varied on a shot to shot basis, a variation in bias current even at the same applied bias-voltage is observed as shown in figure 1 (b). The variation in the bias current is more pronounced in the negative biasing case.

For injecting short pulses of gas-puff during the discharge a piezoelectric valve (MV-112 Maxtek) is used [28]. The valve is located at one of the bottom ports and is toroidally away from the bias electrode, the Mirnov probes and the LPs. Each short pulse of gas puff injects ~ $10^{17} - 10^{18}$ molecules of H_2 depending upon the pulse width and amplitude of driving voltage applied to the piezo valve controlled using a programmable voltage pulsed generator [35].

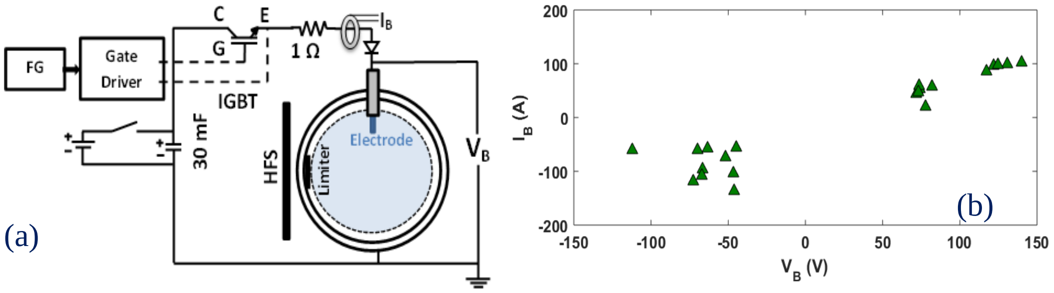

Figure 1: (a) Schematic of Electrode Bias set up used in ADITYA-U tokamak (b) Bias voltage-current characteristics during electrode biasing

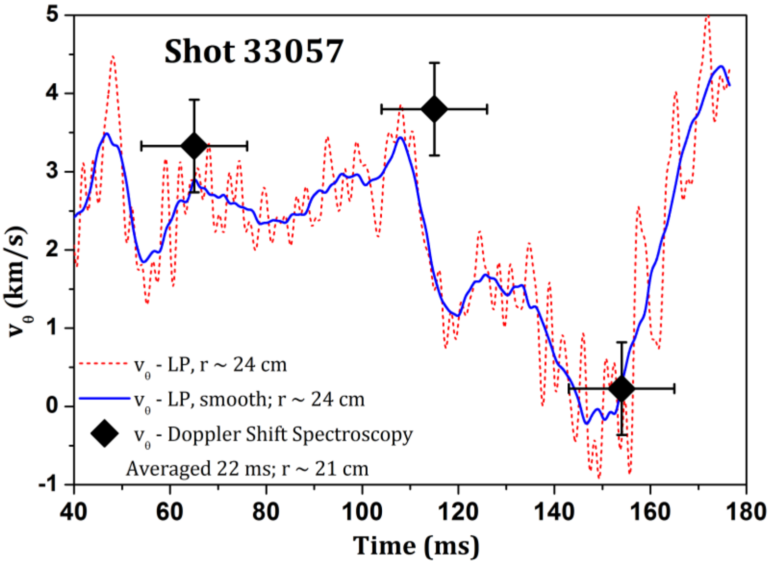

Figure 2: Time evolution of v_θ estimated from E_r measurement at r ~ 24 cm using Langmuir probes for shot 33057 shown in red (dash line) with corresponding plot with smoothed data (blue, solid line). The direct measurement of v_θ from Doppler-shifted C^{2+} spectral line at r ~ 21 cm with each data point averaged over 22 ms is shown in black points; data used from reference #36.

Using the measured radial electric field, E_r, from the LP measurements, the plasma poloidal rotation velocity in the edge region is estimated by $v_\theta = E_r/B_\phi$. With constant B_ϕ, variation in E_r represents the variation in poloidal rotation. The plasma poloidal rotation is routinely measured from the Doppler-shifted emission spectrum of C^{2+} ions at 464.74 nm in the edge region of the ADITYA-U tokamak [36, 37, 38]. The toroidal rotation is also measured using the Doppler-shifted visible passive charge exchange line emission of C^{5+} at 529 nm [38]. The radial profile of radial electric field has been estimated from the toroidal and poloidal rotation measurements and it has been observed that the poloidal rotation has maximum contribution in radial electric field in the edge region of ADITYA-U discharges [36, 38]. However, due to very poor temporal resolution of the spectroscopic system, limited by the exposure time and high CCD readout time [37], it could not be used for capturing the fast changes in the plasma poloidal rotation with the application of the bias-pulse and the gas pulse.

To ensure a one-to-one correspondence between the variations in edge poloidal rotation, directly measured using the Doppler shifted emission spectrum of C^{2+} ion, and that estimated from the edge electric field (E_r) measurements with the LPs, a comparison of the two are plotted for a single discharge (Shot # 33057) in Figure 2. The time evolution of the plasma poloidal velocity for the complete discharge, estimated from the measured radial electric field using Langmuir probes located at $r \sim 24$ *cm* is shown with a red-dashed line in the figure. A five-point smoothened data of the same is also shown with a blue-solid line in the figure. The plasma poloidal velocity measured directly from the Doppler shift of C^{2+} spectral line emission at three different time instances during the same discharge (#33057) is also shown by the filled-diamond symbols in figure 2. The Doppler shift measurements are centred at a slightly different radial location ($r \sim 21$ *cm*) with a radial extent of ~ 3 – 4 cm. Further, the filled-diamond symbols represent the time-averaged value of measured poloidal rotation velocity from Doppler-shift over a time interval of ~ 22 ms, represented by the horizontal error bars in the figure. Each symbol in the figure is time-stamped by adding 11 ms to the start of the exposure time of the CCD. Note that the total integration time of a C^{2+} spectrum measurement is 46 ms (22 ms exposure time + 24 ms readout time of CCD). Figure 2 clearly shows that the poloidal plasma rotation velocity estimated from measured E_r captures the same average variation in rotation velocity as obtained with direct spectroscopic measurements. Therefore, the variations in the plasma poloidal rotation can be determined by measuring the E_r, using LPs and also can be regulated by controlling the E_r.

3. Experimental Results

The temporal evolution of loop voltage, plasma current, bias-voltage and -current pulses along with Mirnov oscillations ($\dot{B_\theta}$) acquired from one of the Mirnov coils (at $\theta \sim 320°$) for a typical discharge of ADITYA-U (shot# 33824) is shown in figure (3a) – (3e) respectively. A train of maximum 5 voltage pulses, each of 5 ms duration has been applied during the plasma current flat-top. Note that the 'slopped edges' in voltage pulses are due to the poor frequency response of the passive attenuator used for voltage measurements. As mentioned earlier, the Mirnov oscillations, poloidal magnetic field fluctuations of a certain amplitude and frequency, are the manifestation of rotating magnetic islands originating from resistive tearing modes (mode numbers $m \geq 2$). The rotation frequency of magnetic island is obtained from the frequency of the Mirnov oscillations. The frequency spectra of MHD oscillations, i.e., the temporal variation of frequency of Mirnov oscillations, are obtained using the analysis function 'specgram' in MATLAB [28]. The figure 3f shows the time-frequency plot (specgram) of the Mirnov oscillations plotted in figure 3e. Note that in order to verify the time evolution of frequency spectra obtained using the 'specgram' routine, independent FFT analysis of Mirnov coil data segments before, during and after the bias and gas-puff pulse periods has also been carried out. The Mirnov oscillations in the typical discharges of ADITYA-U, similar to those used for the presented experiments in this paper, have been analysed thoroughly and are firmly established as majorly related to the m/n = 2/1 Drift-tearing (DT) modes in our previous work [28]. The island structures are identified by singular value decomposition (SVD) analysis of Mirnov oscillations ($\dot{B_\theta}$) acquired by all Mirnov coils, which are also crosschecked by poloidal phase-plots of oscillations from all the coils corresponding to the dominant frequencies present in frequency spectra [28]. The direction of rotation of the modes is also obtained from the phase-plots of the oscillations of dominant frequency [28]. The mode structure related to the Mirnov oscillations spectrum of shot # 33834 shown in Figure 3 is also identified as the m/n = 2/1 DT mode. The m/n = 2/1 mode grows on q = 2 resonance surface, which is located at r ~ 16 – 18 cm (limiter radius = 25 cm) in the discharges analysed for presented study. Hence the m/n = 2/1 mode resides inside the radial location of the electrode-tip in the experiments.

The poloidal rotation velocity of the DT mode is a combination of plasma rotation and the mode's phase velocity in the laboratory frame of reference [6]. The velocity of the DT mode can be represented as: $\overrightarrow{v_{DTM}} = (v_P - v_{\nabla p})\hat{\theta}$, where $\overrightarrow{v_{DTM}}$ is the velocity of the drift-tearing mode in the laboratory frame, $\overrightarrow{v_{\nabla p}} = -\frac{\overrightarrow{\nabla p}\times\overrightarrow{B_\phi}}{nqB^2}$ is the diamagnetic drift velocity and v_P is the plasma velocity in the poloidal (θ) direction. Hence, the DT mode rotation velocity can be influenced by changing the poloidal rotation of the background plasma at the island location. The poloidal rotation of the background plasma can be influenced using several techniques such as by modifying the radial electric field, mainly in the edge region of a tokamak. Furthermore, it is quite well known that rotating the plasma in the edge region changes the plasma rotation in the inside plasma region due to plasma viscosity, mainly through ion-ion collisions [39], as observed in several experiments [24, 40, 41].

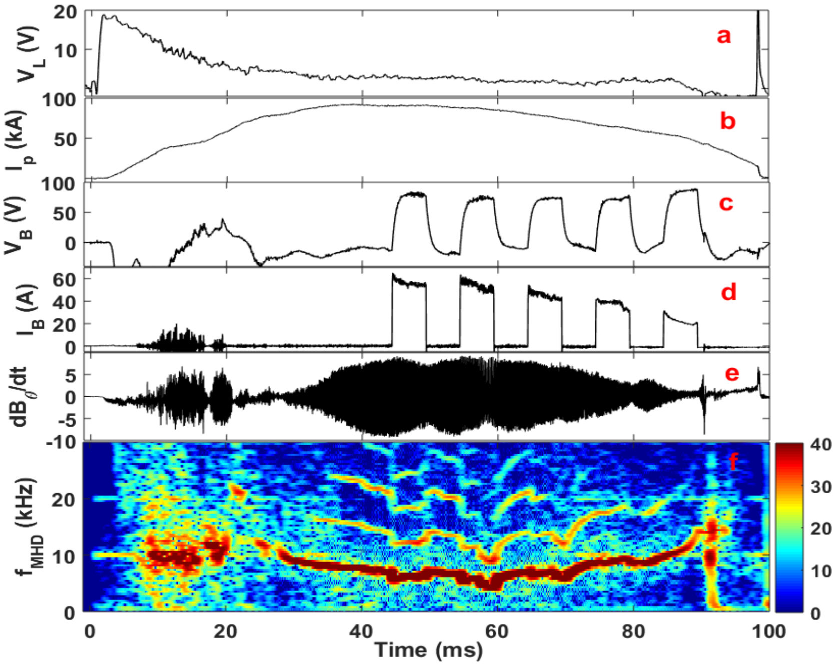

Figure 3: Temporal evolution for discharge # 33824 showing: (a) loop voltage (b) plasma current (c) multiple bias voltage and (d) current, (e) MHD oscillations $\dot{B_\theta}$ from one of the Mirnov coils and (f) Specgram of the MHD oscillation signal.

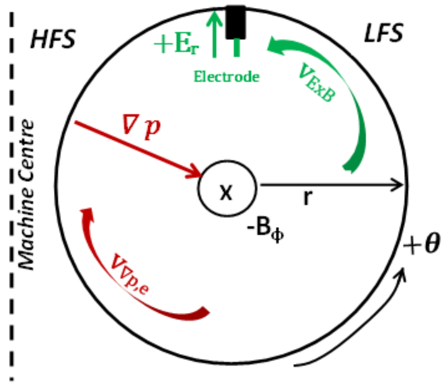

Figure 4: Cartoon depicting the coordinate system and the directions of different fields and gradients. Direction of phase velocity of Drift Tearing Mode and background plasma rotation with $+E_r$ is also shown.

In the experiments presented in this paper, the poloidal plasma rotation is manipulated by the electrode-bias induced radial electric fields. The biased-electrode is placed inside the LCFS of

ADITYA-U tokamak. Under the influence of the bias, the plasma poloidal rotation in the edge plasma region varies due to $\overrightarrow{v_P} = \frac{\overrightarrow{E_r} \times \overrightarrow{B_\phi}}{B^2}$. This variation in poloidal plasma rotation influences the DT mode lying in the vicinity of the electrode radius. With q_{edge} ~ 3 – 4, the m/n = 2/1 resonance surface is located at ~ r = 16 – 18 *cm* [21, 28] in the discharges. And with a spread of a few centimetres of this 2/1 island, the outer boundary of 2/1 island remains in the vicinity of the electrode tip location, r ~ 22.5 *cm*.

In the discharges analysed and presented in this manuscript, the coordinate system and the directions of different fields and gradients are shown in figure 4. The observed MHD modes in these discharges, in the absence of bias voltage, are identified as m/n = 2/1 DT modes, rotating in the electron diamagnetic direction *(-θ)* with a frequency in the range of ∼ 5 – 15 kHz. In case of outward radial electric field ($+\boldsymbol{E_r}$) the $\boldsymbol{E_r} \times \boldsymbol{B_\phi}$ rotation will be in the ion diamagnetic direction *(+θ)*. When positive or negative bias voltage is applied to the electrode, the radial electric field gets modified at the electrode location depending upon the pre-bias plasma potential. This leads to a change in the plasma rotation which subsequently modifies the DT mode rotation.

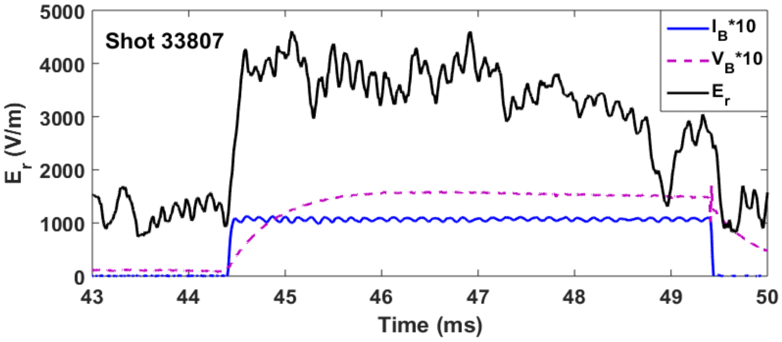

Figure 5: E_r (black solid line) induced due to positively biasing the electrode (magenta dash-line), along with bias current (blue solid line)

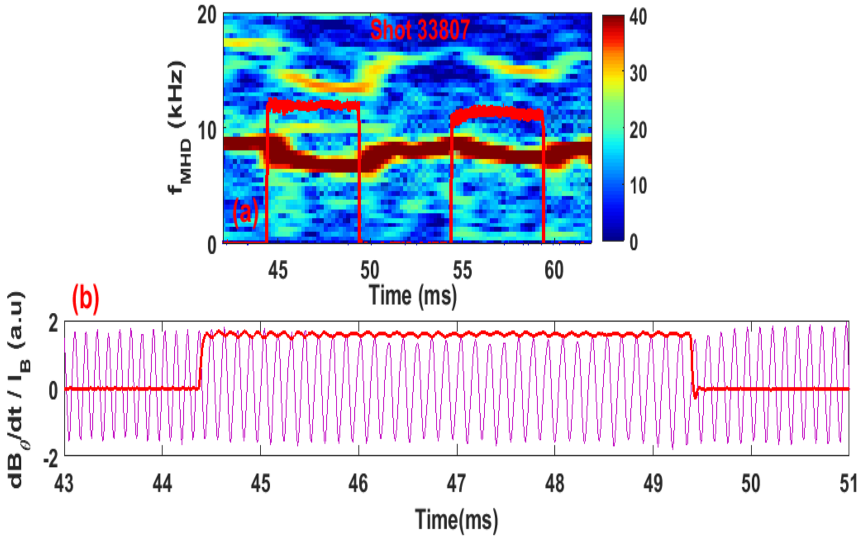

Figure 6: (a) Spectrogram of MHD activity showing variation during the application of positive bias current pulses (red) to the electrode (b) Change in the MHD activity dB_θ/dt (magenta) with bias current (red).

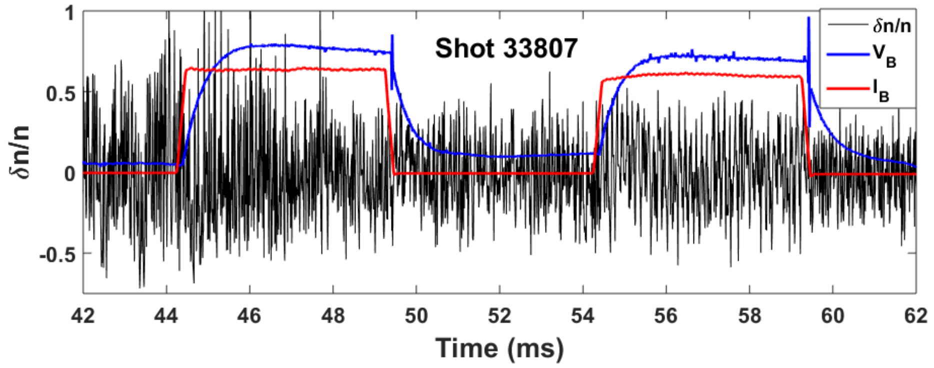

Figure 7: Density fluctuations ($\delta n_e/n_e$) with bias voltage pulses (blue) and current (red)

3.1 Positive Biasing: increasing the plasma poloidal rotation in the ion diamagnetic direction

After ensuring that the edge plasma parameters and the nature of DT modes do not change substantially due to the presence of the biasing electrode in the floating condition, positive bias voltage pulses have been applied to the electrode with the power supply voltage set at ~ 300 V. With the application of the first bias voltage pulse, the potential jumps to ~ + 160 V at the electrode location and the electrode draws ~ 110 A of current as shown in figure 5. The effect of positive bias voltage on the frequency spectra of one of the Mirnov coils is shown in Figure 6a. As soon as the bias is applied the rotation frequency of the DT mode, f_{DTM} gets reduced by 2 – 3 kHz. The change (decrease) in the mode rotation frequency can be seen even by naked eye from figure 6b where the time series data of the poloidal magnetic field fluctuation is plotted before, during and after a bias pulse. The decrease in f_{DTM} occurs within ~ $200\,\mu s$ of the rise of bias current. The mode continues to rotate with reduced frequency throughout the bias pulse, regaining its original (pre-bias) value after the bias is turned off.

The decrease in the rotation frequency of the mode is highest for the first bias pulse. Subsequent bias pulse of ~ +140 V draws ~ 100 A leading to a lesser change of ~ 1 - 2 kHz in the rotation frequency as shown in figure 6a. The changes in the frequency observed in the harmonics of the mode are multiples of the change in frequency of the fundamental mode and hence are more pronounced. Similar observations have been reported for the change in the mode rotation frequency induced by gas puffing [42].

The change in the radial electric field in the edge region due to the application of positive bias voltage has been estimated from the difference in plasma potential ($V_p \sim V_f + 3kT_e$) at two radially separated Langmuir probes. The temporal evolution of radial electric field near (radially outside) the radial location of the electrode is plotted in figure 5. As seen from figure 5, the positive bias increases the radially outward electric field ($+\boldsymbol{E_r}$) by ~ 3 kV/m during the first voltage pulse. This increase in the $+E_r$ causes an increase in the plasma poloidal rotation in the +θ direction by $\mathrm{v}_\theta \sim E_r/B_\phi \sim 3.3\ km/s$ with $B_\phi = 0.9\ T$, opposite to the direction of DT mode rotation. Hence the f_{DTM} reduces by the amount of increase in the plasma rotation frequency of $\sim \mathrm{v}_\theta/2\pi r \sim 2\ kHz$ as observed in the experiments. Note that the density fluctuations ($\delta n_e/n_e$) remain unchanged in the edge region during the bias application, as shown in figure 7, indicating that the drift frequency is not changed with bias and the change in $\boldsymbol{E_r} \times \boldsymbol{B_\phi}$ plasma rotation is mainly responsible for the reduction in DT mode frequency.

3.2 Gas Puffing in presence of positive bias pulse:

Application of a short gas-puff pulse has been observed to reduce the f_{DTM} in ADITYA-U tokamak [28]. A flattening of the pressure profile due to gas-injection thereby reducing the diamagnetic drift frequency has been attributed as the cause for reduction in the mode rotation frequency [28]. Hence to investigate the effect of a gas-puff during the positive bias pulse, a gas-puff pulse injecting ~ $5*10^{17}$ molecules of fuel gas hydrogen is introduced during the application of the positive bias pulse. In shot #33824, a gas-puff pulse is applied after ~ 2.5 ms of the positive bias pulse application as shown in figure 8*a*. The temporal evolution of mode rotation frequency during the application of positive bias along with gas-puff pulse is shown in figure 8b. As described in the previous section, the mode rotation frequency reduces by ~ 2 kHz with the application of positive bias. With the subsequent gas injection, the mode rotation frequency decreases further by 2 – 3 kHz. Hence with the joint application of a positive bias and gas-puff, the DT mode rotation frequency has been brought down by 4 – 5 kHz. The DT mode rotation frequency regains its original value after the effect of gas puff diminishes and the bias voltage pulse is turned off. As discussed in reference [28], the decrease in the mode rotation frequency after gas injection is due to a decrease in the drift- frequency as shown in figure 9a, where the time-series data of the edge density fluctuation is plotted. Figure 9(b) shows the amplitude of the fluctuation in the frequency domain obtained by Fast Fourier Transform (FFT) of the time-series data in two time-windows: before the application of the gas-puff pulse (53.0 – 56.0 ms) and after the application of the gas-puff pulse (57.5 – 60.5 ms). The figure 9(b) clearly shows that the density fluctuations are suppressed after the gas injection. Similar suppression of density fluctuations with gas injection has been reported earlier in ADITYA-U tokamak [28]. A significant suppression in the density fluctuation is observed after the injection of gas puff as shown in figure 9b. These experimental observations provide a crucial evidence of the fact that DT mode rotation observed in the lab frame is due to a combination of the diamagnetic drift and plasma rotation.

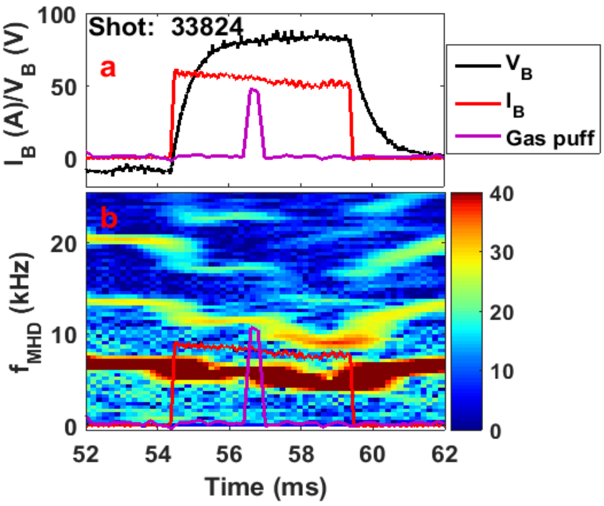

Figure 8: (a) Gas-puff pulse (magenta) introduced during a positive bias voltage pulse (black) and bias current (red) (b) Frequency spectra of MHD oscillations along with bias current (red) and gas puff (magenta).

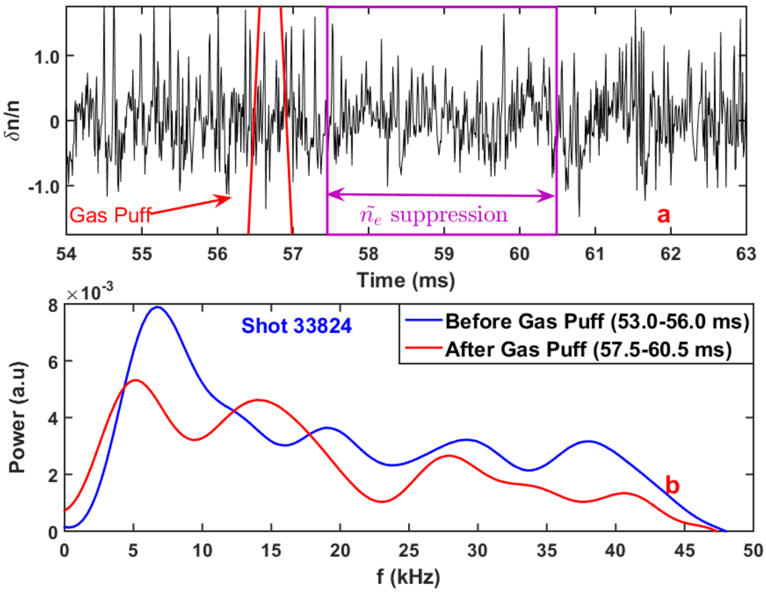

Figure 9: (a) Density fluctuations ($\delta n_e/n_e$) in the edge region with applied gas-puff pulse (red solid-line) (b) Power spectra of n_e before (blue) and after (red) gas puff.

3.3 Negative Biasing: decreasing the plasma poloidal rotation in the ion diamagnetic direction

To further substantiate the results described in the previous section, the rotation velocity of pre-bias edge plasma rotation in the ion-diamagnetic direction has been reduced by applying a negative bias voltage to the electrode. Figure 10a shows that with the application of bias voltage the potential decreases to ~ -50 V at the electrode location (applied voltage ~ -140 V) and ~ 80 A of electrode current is drawn. Biasing the electrode negatively reduces the pre-bias radially outward radial electric field ($+\boldsymbol{E_r}$), which in turn slows down the pre-bias plasma poloidal rotation in the ion diamagnetic direction, i.e., in the + θ direction. This leads to a reduced opposition to the DT mode rotating in electron diamagnetic direction prior to biasing and an increase in the f_{DTM} as shown in figure 10b, where the temporal evolution of frequency spectra of the poloidal magnetic fluctuations is plotted. The figure 10b clearly shows that the f_{DTM} increases as soon as the negative bias voltage is applied to the electrode. With the application of negative bias voltage, the pre-bias radially outward electric field decreases by ~ *1 – 1.5 kV/m* as shown in figure 10c, reducing the pre-bias plasma poloidal rotation in ion-diamagnetic direction by *1-1.5 km/s*. Also shown is the time evolution of E_r which has been smoothed to provide a better representation. The observed increase in the magnitude of the f_{DTM} ~ *1-1.5 kHz* agrees well with the decrease in plasma rotation frequency in the ion-diamagnetic direction. Hence by changing the bias polarity, the DT mode rotation frequency can be either decreased or increased in ADITYA-U tokamak. Interestingly, in the case of a negative bias, the DT mode rotation frequency does not come back to its pre-bias value after the bias voltage is switched-off as it did in case of positive bias.

3.4 Gas Puffing in presence of negative bias pulse:

The increase in the DT mode rotation frequency due to negative bias application has been observed to be again reduced by hydrogen gas injection during the negative bias pulse. It has been observed that with the gas injection, the f_{DTM} reduces to its pre-bias value. The bias voltage pulse and the bias current are shown in figure 11a, whereas, the frequency-time plot of the poloidal magnetic field fluctuations is shown in figure 11b, along with the inverted bias-current. As can be clearly seen from figure 11b, the negative bias increases the f_{DTM}

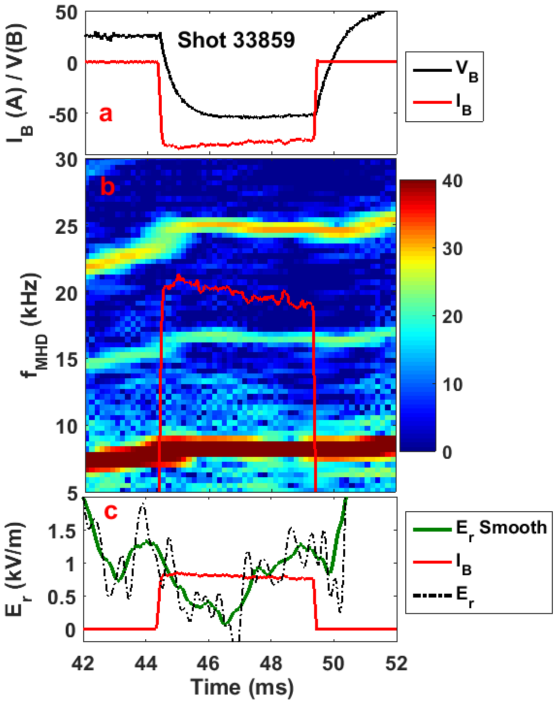

Figure 10: (a) Bias current (red) and bias voltage (black) (b) Frequency spectra of MHD oscillations along with bias current (inverted red line) (c) Measured E_r (black), smoothed E_r (green) with the bias current (red, inverted) in case of negative bias.

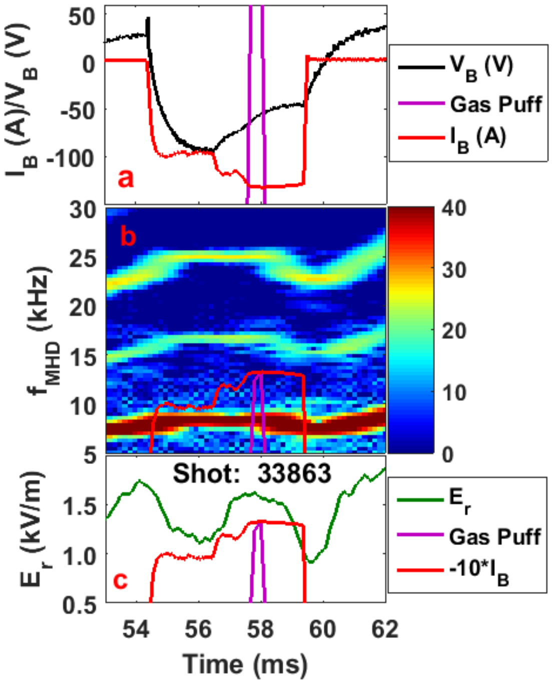

Figure 11: (a) Gas puff (magenta) applied during negative bias current (red) and bias voltage (black) (b) Frequency spectra of MHD oscillations along with gas-puff pulse (magenta) and bias current (inverted, red) (c) Measured E_r (green) with the bias current (red) and the gas-puff pulse (magenta).

by ~ *1.5 kHz*, which is reduced to its pre-bias value due to the gas injection. Figure 11c shows the variation in the radial electric field due to negative biasing and gas-puff. The pre-bias radial electric field in the radially outward direction decreases with the application of the bias voltage leading to a reduction in the plasma poloidal rotation in the ion-diamagnetic direction and hence the f_{DTM} increases. However, even though it has been observed that the radially outward electric field reduces with the gas injection too, the f_{DTM} decreases. This indicates that the diamagnetic drift has the dominant influence on the DT mode rotation in comparison to the E × B rotation as also reported by Raj et al. [28].

3.5 Statistics:

The bias voltage has been varied to change the magnitude of induced radial electric field and hence the plasma rotation velocity to study the variations in the magnitude of the DT mode rotation frequency. The observed incremental variation in DT mode rotation frequency, δf_{DTM} at different bias-voltages of both the polarities is plotted in figure 12. In case of positive bias a minimum potential change of ~ 75 V at the electrode location is required in our experiments to bring a change in the DT mode rotation frequency. Whereas in the case of negative bias, ~ - 40 V is sufficient to influence the DT mode rotation frequency. The DT mode rotation frequency is found to increase almost linearly with the increase in the applied potential at the electrode location and the maximum variation in the DT mode rotation frequency δf_{max} is observed with potential variations in the range of 100 – 150 V at the electrode location in both the polarities. The plasma is disrupted when potential variations above ~ 150 V are attempted in both polarities.

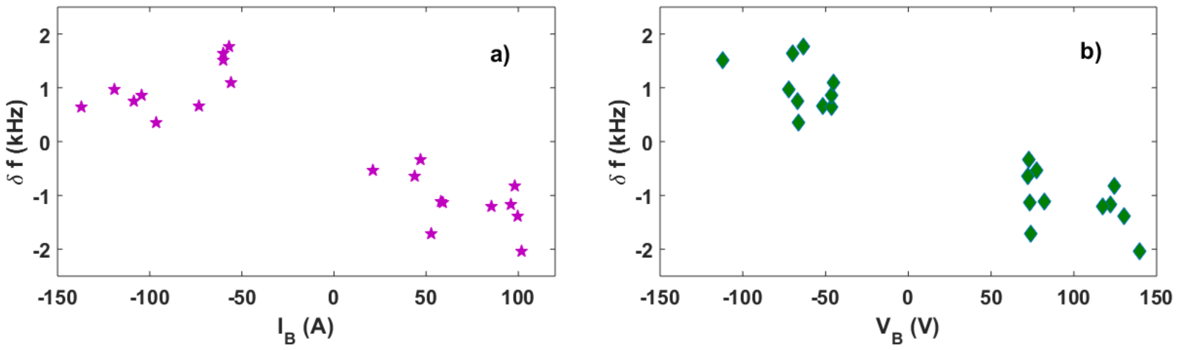

Figure 12: Change in the rotation frequency of drift tearing mode with a) bias current and b) bias voltage

4 **Discussion and Summary**:

In ADITYA-U tokamak, the application of a positive (negative) voltage to an electrode placed in the edge plasma region, inside the LCFS, led to a decrease (increase) in the mode rotation frequency of the m/n = 2/1 drift-tearing modes. As expected, the positive (negative) bias sets up a positive (negative) radial electric field in the edge region which increases (decreases) the pre-bias poloidal rotation velocity of the plasma in the ion-diamagnetic direction. The establishment of a poloidal plasma rotation driven by a biased-electrode induced radial electric fields has been known for long [41]. The experimental observations described in section 3, demonstrate a strong relationship between the rotation frequency of the DT mode and the plasma poloidal rotation driven by a biased-electrode induced radial electric field. The DT mode rotation frequency can be changed either by stabilizing the mode due to induced rotation shear or rotating the background plasma through $\boldsymbol{E_r} \times \boldsymbol{B_\phi}$ plasma rotation in which the mode rotates. Strongly sheared plasma flow is quite well-known for stabilizing the MHD modes in tokamaks and is extensively studied, both theoretically and experimentally. However, in our experiments, significant variations in f_{DTM} have been observed even in the case of reduced shear in plasma rotation (dv_θ/dr), as biasing the electrode (fixed at one radial location inside LCFS) negatively reduces the radial electric field and its shear. Since the mode rotation frequency is observed to decrease with positive bias and increase with negative bias, the change in background plasma rotation seems to be more responsible for causing it. Note that the magnitude of the DT mode does not vary significantly in both biased polarities further indicating that apparently there is no change in the mode stability. However, when the mode rotation frequency decreases by 25 % (~ 2 kHz out of ~ 8 kHz) in the case of positive bias, the voltage acquired by a Mirnov probe should

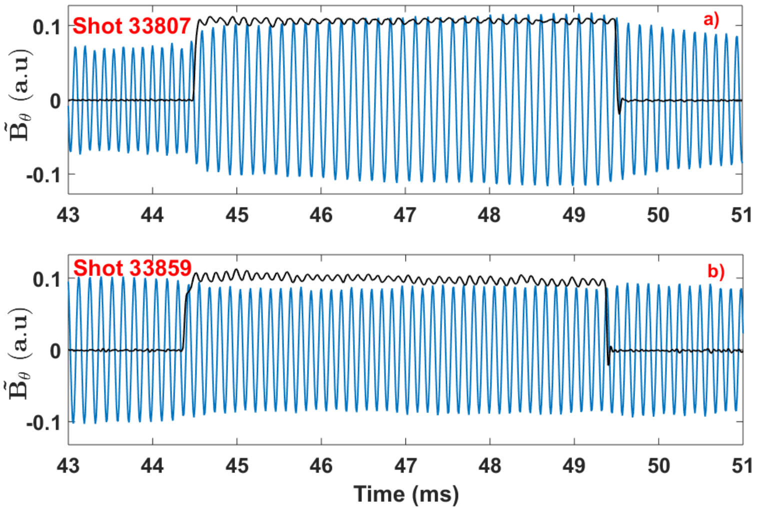

Figure 13: Change in amplitude (blue) of DTM with bias current (black) for a) Positive bias and b) Negative bias. Bias current in b) is inverted.

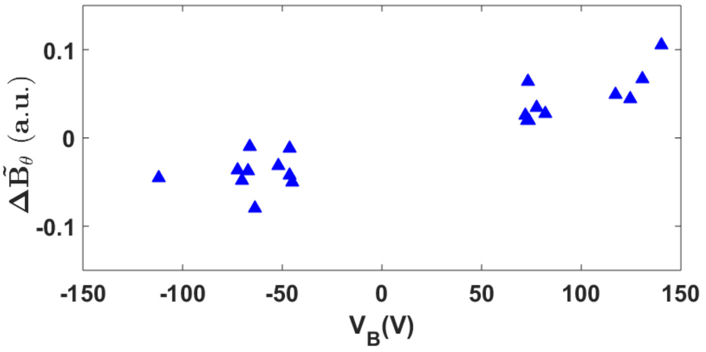

Figure 14: Change in the amplitude of drift tearing mode with bias voltage.

also be reduced by 25 % as the voltage output of the Mirnov probe is proportional to the frequency of the rotation. The lack of change in the amplitude of the oscillations then indicates that the voltage has increased approximately by the same amount as it would have been reduced due to frequency reduction. This implies that the mode is destabilized and has grown in magnitude due to reduction in its rotation velocity. This is further verified by directly integrating the Mirnov probe data (dB_θ/dt as a function of time) to obtain the poloidal magnetic field fluctuation. The temporal evolution of poloidal magnetic field fluctuations ($\widetilde{B_\theta}$) for shot #33807 and #33859 is plotted in figure 13a and 13b respectively, where the bias current pulse is also shown. It can clearly be seen from the figure that with the application of positive bias, the amplitude of poloidal magnetic field fluctuations ($\widetilde{B_\theta}$) increases and remains elevated during the complete bias pulse in fig 13a. This observation clearly proves that as the mode rotation frequency decreases due to the application of positive bias-voltage the mode amplitude grows, which is quite in line with the theoretical predictions. Similarly, in the case of negative bias, an increase in mode rotation frequency leads to a reduction in the amplitude of poloidal magnetic field fluctuations ($\widetilde{B_\theta}$), as shown in fig 13b, indicating that the mode has damped. The variation of the amplitude of $\widetilde{B_\theta}$ fluctuations with different bias voltages, both positive and negative, is shown in figure 14. These observations clearly suggest that the growth rate of DT modes is influenced by the bias-induced plasma poloidal rotation. Furthermore, it can be seen from figure 5b, that the change in DT mode rotation frequency occurs within ~ 100 – 200 μs of the application of the bias voltage. Similar observation of rapid response of biasing on mode rotation frequency of the 2/1 tearing mode has been reported in J-TEXT tokamak [24, 40]. It is quite possible to rotate the plasma poloidally through $\boldsymbol{E_r} \times \boldsymbol{B_\phi}$ rotation. As seen in figure 5, after the application of the bias voltage, the radial electric field changes in ~ 100 - 200 μs. The radial electric field is modified due to the flux-surface charging by the electrode. It has been shown in ADITYA tokamak using a leaky-capacitor model [43] that the flux surface can be charged in ~ 100 – 200 μs by biasing an electrode placed inside the plasma. Since, no significant variation in the density fluctuations has been observed with the application of bias of either polarity in the experiments, the change in the DT mode rotation frequency may not be due to change in diamagnetic drift frequency. However, when the diamagnetic drift frequency has been varied through a short gas-puff pulse in the presence of bias voltage of either polarity, the DT mode rotation frequency is influenced accordingly almost independently of the background plasma rotation. As the gas-puff reduces the diamagnetic drift frequency, an additional reduction in the DT mode rotation frequency has been observed in case of positive bias. Whereas the increase in the DT mode rotation frequency due to negative bias has been observed to be balanced by the reduction in the diamagnetic drift frequency leaving the mode rotating at the pre-bias frequency. Note that with the value of q_{edge} being ~ 3 – 4 in the discharges analysed and presented in the manuscript, the 2/1 resonance surface is located at ~ r = 16 – 18 cm [21, 28]. With a spread of few centimetres of this 2/1 island, the outer boundary of 2/1 island remains in the vicinity of the electrode tip location. Furthermore, the radial electric field modification by the biased electrode modifies the plasma rotation in the poloidal direction through E_r x B_Φ. This modification in poloidal plasma rotation influences the rotation of the 2/1 mode and hence its rotation frequency changes as observed in the experiments. Modifications in the edge region influencing the magnetic islands located radially inside from the edge region may also be due to toroidal coupling effects analogous to what is reported in [44]. Similar observations have been reported earlier too in other biasing experiments in ADITYA [21] and other tokamaks [24, 26, 40, 45].

In summary, the influence of bias-electrode induced $\boldsymbol{E_r} \times \boldsymbol{B_\phi}$ plasma poloidal rotation on the mode rotation frequency of the drift-tearing mode is studied in ADITYA-U tokamak. The magnitude of this $\boldsymbol{E_r} \times \boldsymbol{B_\phi}$ poloidal rotation velocity has been changed by changing the bias polarity. A reduction (increase) of ~ 1 - 3 kHz in the DT mode rotation frequency has been observed by rotating the plasma poloidally in the ion-diamagnetic direction with different velocities. Along with that the DT mode rotation frequency is also modified by reducing the diamagnetic drift frequency by gas injection. It has been observed that the total change in DT mode rotation frequency is a vector addition of the changes incurred by the two processes, i.e., the change in the poloidal rotation and the change in the diamagnetic drift frequency. Our experimental results corroborate the experimental findings in J-TEXT tokamak [40] where it had been speculated that the direct interaction between the magnetic island and edge plasma layer could be a candidate mechanism for the rapid response of the 2/1 tearing mode to electrode biasing. Additionally, our results also demonstrate that the drift tearing mode rotation frequency can be effectively controlled by controlling the plasma rotation.

Acknowledgement and Author Contributions:

This work has been carried out as part of the PhD work of the first author, registered in HBNI, Mumbai. He has conceptualized, designed and carried out the experiments, designed, fabricated and installed the electrode biasing set up and its power supply, constructed the probes, analysed the results, prepared the original draft and edited the later versions and is the primary contributor of the work. The authors greatly acknowledge the help from ADITYA-U tokamak team of the Institute for Plasma Research, Gandhinagar, India, for conducting the experiments. The authors would like to thank the IPR workshop for fabrication of the Langmuir probes and ceramic assembly for the electrode bias set up.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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