Origin of Harmonics of Drift Tearing Mode in ADITYA tokamak

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Abstract

Tearing modes play pivotal role in determining two of the most critical parameters for tokamak operation, namely plasma confinement and disruption. They have been extensively studied both theoretically and experimentally, as controlling them is foremost priority for every tokamak, including ITER and future large size tokamaks. Coupling of tearing modes with drift wave is a common phenomenon observed in all tokamaks, resulting in drift tearing modes. Multiple drift tearing modes have also been observed in a bunch of experiments. However, these modes have been identified as different modes with different poloidal (m) and toroidal (n) mode numbers. In ADITYA as well as ADITYA Upgrade tokamak, the frequency spectra of Mirnov signal show multiple frequency bands corresponding to drift tearing modes. Interestingly, the higher frequencies have been precisely found to be integral multiples of the fundamental frequency. Further analysis reveals that these frequencies don’t belong to different modes but harmonics of a single mode. These harmonic frequencies also reflect significantly in the density as well as impurity radiation. We have also found that the occurrence of these harmonics is strongly correlated with the presence of runaways in the plasma. The origin of these harmonics and their operational regime will be explained in this paper.

1. Introduction

Tearing modes play pivotal role in determining two of the most critical parameters for tokamak operation, namely plasma confinement and disruption. Resistive tearing modes are relatively slower growing modes than ideal tearing modes, but they are tougher to get rid of in comparison of ideal MHD modes which can be avoided by tailoring the current profiles [1]. The resistive tearing modes can be stabilised/saturated at finite island width due to stabilising effects of toroidal curvature and compressibility in tokamaks. They can significantly degrade the plasma confinement by creating magnetic islands which are physical tearing in magnetic flux surfaces. These islands enhancing cross field particle transport hence limit the maximum attainable confinement time for tokamaks. In worse cases, when their growth rate isn’t controlled the islands keep growing and destroying more and more flux surfaces, ultimately leading to plasma disruption which is extremely dangerous for plasma facing components of tokamaks. To our relief these tearing modes usually get stabilised by toroidal curvature or coupling with other modes like drift modes. Drift modes are global modes which exist in plasma due to the radial density gradient of charged species in tokamaks. Coupling of tearing modes with high frequency drift modes is a common phenomenon observed in many tokamaks including ADITYA, which results in drift tearing modes. The coupling of drift mode to tearing mode is reduce the growth rate of the tearing mode, in general, leading to mode saturation. Their frequencies, generally lie between 5-15 kHz. These modes are being extensively studied both theoretically and experimentally, as predicting and controlling them is an utmost priority for successful operation of tokamaks, including ITER and future large size tokamak reactors. The dynamics of drift tearing modes has been extensively explored in a wide range of discharges in ADITYA tokamak. It was a medium size (R0 = 75 cm, a = 25 cm), limiter tokamak which has recently been upgraded to ADITYA-Upgrade with a diverter configuration. In both ADITYA [1] and ADITYA-Upgrade [2] tokamak, we have frequently observed and studied these tearing modes with frequencies 5-15 kHz. Magnetic fluctuations are detected using a set of 16 Mirnov coils distributed with equal poloidal separation, at one toroidal location. It has been observed that the tearing modes are coupled to drift modes at frequencies lower than a threshold frequency spectrum of MHD activity of these discharges show multiple frequency bands which we suspect to be higher Harmonics of the drift tearing modes. There is a threshold in MHD amplitude as well for observation of drift tearing mode Harmonics. Also, in discharges with such modes the mode frequencies have been significantly modulated by modulating edge density through gas puffing. In this paper we have explored various experimental evidence of drift tearing mode and its harmonics and their frequency space. We have also observed sudden transit of a single tearing mode to drift tearing mode with several harmonics due to runaway electron dynamics.
The following section 2 explains the experimental conditions and diagnostics used for this study, in section 3 we present experimental observations in detail and later in section 4, we have discussed the physics interpretation of our experimental evidences and a probable mechanism behind origin of these Harmonics. Finally we summarise our study in section 5 and mention future scope of this study.

2. Experimental setup

ADITYA was a medium size, ohmically heated limiter tokamak, which has been upgraded to ADITYA-Upgrade tokamak with diverter configuration. This paper includes observation of discharges from both ADITYA and ADITYA-U which fall in category of drift-tearing modes, in limiter operation/mode. Both the machines have major radius, R~75 cm and minor radius, a ~25 cm. Typical plasma parameters of the discharge used for study presented in this paper are: plasma current, Ip ~80-120 kA, chord average plasma density, n_e ~ 1.5-3 x 10^{19} m^{-3}, electron temperature, T_e ~300-700 eV characteristics, current flat-top duration, 50-200 ms, toroidal field, B_T ~ 0.8-1.2 T and pre-fill pressure ~ 10^{-5} (ADITYA) and 10^{-4} torr (ADITYA-U). In Figure 1 we have shown temporal evolution of basic plasma parameters of a typical discharge in ADITYA tokamak.

![Figure 1](image-url)  
**Figure 1**: Plot showing time evolution of (a) Loop voltage (b) Plasma current and gas puff pulses (c) Hα emission intensity and (d) MHD activity picked by Mirnov coil for a typical plasma discharge (#29078) with strong MHD activity.

In the both ADITYA and ADITYA-U tokamak, the MHD oscillations have been measured by similar set of 16 Mirnov coils located at poloidal periphery inside the vessel wall, with equal angular separations at a single toroidal location (ADITYA) two poloidal location at separation of 180 degrees toroidally. These probes are placed at r = 26.5 cm and have a linear frequency response up to 50 kHz (ADITYA) and 100 kHz (ADITYA-U). The plasma density and its radial profile is measured by microwave interferometer with seven-channel at fixed frequency O-mode, and acquisition frequency 100 kHz. Soft X-ray (SXR) emission from discharge plasma are detected with a pinhole camera with an array of six surface barrier detectors (ORTEC, active area ~ 50 square mm, thickness ~ 100 μm) for both ADITYA and ADITYA-U. This pinhole camera measurements are also used to estimate core electron temperature using Beryllium foils of different thicknesses. Another surface barrier detector used to monitor the integrated SXR emission which is collimated to view emission from core plasma of radius ~ 8.5 cm [4]. Edge and SOL density and temperature are measured by set of radially and poloidally distributed Langmuir probes in ADITYA-U. The Hard X-ray emission due to extremely energetic runaway electrons [5] is detected by a 3 inch diameter NaI (TI) scintillator detector, which is a lead-shielded scintillator, collimated to see the radiation mainly from the limiter at one toroidal location. Visible spectrometer and photomultiplier tubes with wavelength filter have been used to detect neutral and impurity line radiations for both ADITYA and ADITYA-U.
3. Experimental Observations

Strong MHD activity have often been observed in majority of experiments in ADITYA as well as ADITYA Upgrade tokamak through set of Mirnov coils. Various techniques like singular value decomposition (SVD), specgram (MATLAB), phase correlation, and bi-coherence analysis of multiple Mirnov channels are used to investigate the MHD activity for various plasma discharges. In tokamak different MHD modes have different characteristic frequencies. To understand the evolution of MHD modes in a discharge systematic spectral analysis of poloidal magnetic fluctuation ($B_\theta$) acquired by 16 Mirnov coils has been executed for a large number of discharges. The ‘specgram’ (R) function in MATLAB has been used for this purpose. It basically divides the $B_\theta$ data into a number of small data windows with 256 data points in each window (using hanning window). Every subsequent window overlaps 230 data points the previous window. It then executes FFT and gives the frequency amplitude/power as a function of frequency for each data set. The final plot is a colormap image with frequency value on its Y axis, time on its X axis, and the magnitude of each frequency is reflected by a colour code (‘JET’ type), where red corresponds to the highest power and blue corresponds to the lowest. Results from specgram of the MHD data has revealed presence of multiple distinct frequency bands which persist through majority of the current- flat top as shown in figure 2. It can be seen clearly in figure 2, that the mode onset precedes the current flat top, the mode frequency simply evolves according to the discharge parameters through-out the flat top.

![Figure 2](image)

Figure 2: Plot showing time evolution of (a) Plasma current (blue) and loop voltage (orange), (b) MHD activity picked by Mirnov coil and its (c) frequency spectrum with multiple frequency bands in along with gas puffs (blue) in discharge #29078.

3.1 Identical frequency behaviour of different discharge parameters

The raw data of several other plasma parameters like soft X Ray (SXR), density also exhibited broad bands in time corresponding to strong MHD activity for majority of the discharges. This feature was absent in discharges with low MHD activities. Frequency power spectrum of plasma density coincided significantly with that MHD fluctuations. Figure 4 shows power spectrum of frequencies for shot #29891 from ADITYA tokamak. The power peaks at ~6.5 kHz, 12.5 kHz and 19 kHz respectively for both density and MHD. The temporal evolution of frequency spectrum of density, SXR, neutral (Ha) as well as impurity (OII, CIII) line emission intensity also exhibit identical frequency bands. Figure 3 shows time evolution of frequency spectrum for of density, SXR, neutral (Ha) and impurity (CIII) for a typical discharge #29078 with such multiple frequency bands.
Figure 3: Plot showing power spectrum of MHD fluctuation and density for shot #29891 (ADI)

Figure 4: Plot showing time evolution of identical frequency bands in specgram of (a) Mirnov 5 data, (b) Mirnov 16 data, (c) plasma density, (d) Central Soft X-Ray channel, (e) Hα and (f) CIII impurity emission intensity

This signature of identical frequencies in other plasma parameters as well as multiple frequency bands is never observed in regular plasma discharges with low MHD activity, which mostly exhibit single MHD mode.
3.2 Instantaneous modulation in all frequency band by application of gas puffs

Interestingly, the higher frequencies have been found to be precisely the integral multiples of the fundamental frequency, for all the discharges with these characteristic. Generally, these modes are identified as different modes with different poloidal (m) and toroidal (n) mode numbers. In ADITYA as well as ADITYA-U, gas puffing is extensively used to maintain plasma density, during current flat top. The gas puffs are pre-programmed according to the experimental requirements. For the present study we have used periodic gas puffs with varied magnitude. The neutrals injected through the gas puffs in moderate amount suitable for the plasma discharge. These gas puffs have been observed to modulate the MHD amplitude (figure 1) as well as mode frequency. Experiment show that the higher harmonic frequencies are also modulated along with the fundamental mode. The decrease in frequency due to gas puffing effect is also proportional to their n (harmonic) number (Figure 2).

3.3 Relation between fundamental frequency and number of higher harmonics

Extensive data analysis of a number of discharges reveal that the tearing modes couple with the drift modes at frequencies lower than a certain threshold. Interestingly the number of observed higher Harmonics is found to be inversely proportional to the frequency of fundamental mode. In Figure 4 we have plotted the number of higher harmonics observed in frequency spectral evolution with respect to the fundamental frequency of the drift mode.
In figure 5, we have plotted time evolution of MHD frequency spectrum for a single discharge with multiple frequency bands in which more numbers of higher frequency appears as the fundamental frequency value decreases. We can see that initially 3 frequency bands onset at ~20 ms into the discharge with frequency values, the higher frequencies disappear after 30 ms. It should be noted that as the fundamental frequency of mode decreases from 12-13 kHz to 9-10 kHz, 4 higher harmonics appear in the frequency specgram. The statistical analysis also reveals that the MHD amplitude as acquired by mirnov also has a threshold value for observation of Harmonics. The Harmonics appear when the MHD amplitude exceeds a threshold which indicates towards parametric coupling of drift tearing modes which may be a possible cause of harmonics generation.

Figure 5: Plot showing (a) plasma current and (b) MHD frequency evolution displaying appearance of more frequency bands as the fundamental frequency goes from 12-13 kHz to 9-10 kHz for #30629 in ADITYA-Upgrade

4. Discussion
A certain regime of discharges in ADITYA and ADITYA-U exhibit strong long lived MHD activity through majority of plasma flat top. The frequency analysis of poloidal magnetic fluctuation of these discharges acquired by multiple Mirnov coils reveal presence of multiple frequency band. All the characteristics of these modes have been discussed in the preceding section. These frequency bands have been attributed to Drift-tearing modes because of the following reasons:
1) The discharges exhibit identical frequency bands in several diagnostics other than magnetic probes like density, SXR, neutral (Ha) and impurity (CIII). This indicated that the MHD mode is coupled with an electrostatic mode as well.
2) The frequency of the fundamental band, perfectly matches the drift frequency for ADITYA parameters, i.e. 5-15 kHz.
3) These frequencies are present in all radial SXR as well as interferometer, indicating the non-local nature of these modes.
4) These MHD modes have been significantly modulated in frequency as well as amplitude by gas puff, which further indicates that they are coupled with a density driven instability i.e. drift modes.

4.1. Different modes or Harmonics of a single mode:
The number of frequency band observed in MHD frequency spectrum time profile went as high as 7 in some discharges in ADITYA as well ADITYA-U tokamak. Following are the reasons behind attributing the multiple frequency bands to higher harmonics of the same drift tearing mode.
1) The higher frequencies always appear as multiple of the fundamental mode frequency and remain so throughout the discharge for each and every discharge with belongs to above mentioned MHD regime.
2) The higher modes are instantaneously modulated along with the fundamental mode, by application of gas puff.

4.2. Origin of Harmonics:
The most probable theory that fits our experimental observation of harmonics of drift tearing mode is parametric coupling. The bicoherence analysis of these MHD modes show clear signature of non-linear self-interaction of different mode as well as interaction between harmonics.
The bicoherence analysis is a method to measure the extent of non-linear coupling between different frequencies present in a single signal. It is only large when the phase between the wave at \( \omega \) and the sum wave \( \omega_1+\omega_2 \) is nearly constant over a large number of data segments (windows) selected for the analysis. The red points observed in the bicoherence spectrum indicate frequencies interacting non-linearly. The bicoherence plot shows that fundamental frequency of 7-8 kHz is non-linearly interacting with itself to generate higher harmonic modes. The plot also reveals that higher harmonics also interact with the fundamental harmonic modes as well as other harmonic modes. Further analysis of the temporal evolution of coupling and power distribution between different harmonics may provide significant insight of the non-linear dynamics of drift tearing modes.

Figure 6: Plot showing time evolution of (a) Plasma current (Blue) and MHD fluctuation (a.u.) (orange) (b) specgram of MHD and (c) bicoherence plot for MHD data in 50-70 ms for #30629 in ADITYA-U

5. Conclusion:
A plasma discharge regime exhibiting strong MHD activity is obtained in ADITYA as well as ADITYA-U tokamak. The study presented in this paper reveals that these MHD modes exhibit rich non-linear MHD interactions. The frequency spectrum evolution of MHD data from several tokamaks display presence of multiple
frequency bands, which sometimes are attributed to different modes and sometimes passed as harmonics. A thorough understanding of these MHD modes are essential in order to develop a reliable MHD prediction, control and mitigation methods. The study presented in this paper suggest that these MHD modes are drift tearing modes which non-linearly interact with themselves to create higher harmonics, which we see as higher frequency bands in frequency spectrum. It has been observed that for lower fundamental frequency mode larger number of harmonics are observed, which indicates parametric dependence behind the occurrence of harmonics. In future the time evolution of bispectrum would be further analysed in order to understand power distribution amongst different harmonics which can reveal some interesting physics of non-linear self-interaction of MHD modes.

References: