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Non-Linear Phenomena of Energetic-Ion-Driven MHD Instabilities in LHD

YAMAMOTO Satoshi[1], TOI Kazuo, OHDACHI Satoshi, NAKAJIMA Noriyoshi, SAKAKIBARA Satoru, OSAKABE Masaki, YAMADA Hiroshi, MASUZAKI Takashi, WATANABE Kiyomasa, NARUSHIMA Yoshiro, TAKEIRI Yasuhiko, NARIHARA Kazumichi, YAMADA Ichihiro, KAWAHATA Kazuo, TANAKA Kenji, TOKUZAWA Tokihiko, MORITA Shigeru, GOTO Motoshi, OHYABU Nobuyoshi, and LHD Experimental Groups I / II

National Institute for Fusion Science, Toki 509-5292, Japan

[1] Dep. of Energy Eng. and Science, Nagoya University, Nagoya 464-01, Japan

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Abstract

Energetic ion driven MHD modes were observed in NBI heated plasmas of LHD. The observed modes are classified into three kinds of modes, depending on the frequency range, degree of amplitude modulation (continuous or bursting) and temporal evolution of the mode frequency with or without rapid frequency chirping. It is important and of interest to study these phenomena related to non-linear wave-particle interactions. We have investigated the excitation conditions of continuous and bursting TAEs. Continuous TAEs are only observed just above the threshold. When drastic TAE bursts are excited, about 15 % of the beam power is lost by each burst. This suggests that the bursting TAEs induce energetic ion transport before the thermalization. Two kinds of frequency chirping were observed in NBI heated plasma. One is rapid frequency chirping, of which chirping time scale is much shorter than a characteristic time of the change of the plasma equilibrium, and the other is slow frequency chirping.

Keywords:

energetic ion, TAE, non-linear, MHD instability, transport of energetic ion

1. Introduction

MHD instabilities destabilized by the energetic ions are being studied in many magnetic confinement devices, because they might considerably degrade the confinement of α-particles and damage the wall in a fusion reactor. Furthermore, the studies of energetic ion driven MHD instabilities are important and of interest to clarify the mechanism of non-linear wave-particle interactions. Non-linear phenomena related to these MHD instabilities such as bursting behavior, saturation of mode amplitude, frequency chirping and spectrum splitting were observed in many devices [1-5]. The bursting behavior and saturation of these MHD instabilities may be qualitatively explained by "predator-prey relationship" model in certain experimental conditions [1]. When the instability ("predator") is destabilized by the energetic ion population ("prey"), energetic ions would be expelled from the plasma confinement region and/or the energetic ion density profile would be redistributed. Then, the instability is stabilized because the energetic ion population and the spatial gradient are not large enough to destabilize them. This cycle is repeated, as far as energetic ions are continually supplied. However, the frequency chirping and spectrum splitting cannot be explained by the

Corresponding author's e-mail: syama@nifs.ac.jp

simple predator-prey model. Much more complex and sophisticated theories or numerical simulations are required [6].

In NBI heated plasmas of LHD, various energetic ion driven MHD instabilities were observed [4,7]. The following three kinds of MHD modes, toroidicity induced Alfvén eigenmodes (TAEs), global Alfvén eigenmodes (GAEs) with toroidal mode number $n = 0$ and resonant TAE (R-TAEs) or energetic particle modes (EPMs) are identified in the recent experimental studies. TAEs reside in the TAE frequency gap which is formed by the coupling of cylindrical Alfvén spectra with different poloidal mode number m and $m + 1$ induced by finite toroidicity. When the mode frequency is appreciably less than the TAE gap and intersects the shear Alfvén continua, TAE would suffer from strong damping due to the continuum damping. In this situation, TAEs will be stabilized. However, when the energetic ion drive of the mode is large enough to overcome various damping mechanisms, R-TAEs or EPMs would be unstable [8,9]. R-TAE is a beam-like mode of which frequency is mainly determined by the wave-particle resonance condition and is usually less than the TAE gap frequency.

2. Experimental Setup

LHD is a heliotron type device with $l = 2$ field polarity and the toroidal field period of $M = 10$. In the studies of energetic ion driven MHD instabilities, the toroidal magnetic fields strength and magnetic axis position are respectively varied in the range of $B_t = 0.5 - 2.9$ T and $R_{ax} = 3.5 - 4.05$ m. The energetic ions are produced by the tangential NBI up to 6 MW with the beam energy up to 160 keV hydrogen. The velocity of injected ions can easily become super-Alfvénic velocity even in relatively low density at lower magnetic field $B_t < 1.5$ T. The primary fluctuation diagnostics for these studies are two types of toroidal and helical array of magnetic probes, of which frequency response is up to 600 kHz. The toroidal array of six magnetic probes is used to determine the toroidal mode number (n), and the helical array of twelve probes is used to determine the poloidal mode number (m) using the toroidal mode number obtained from the toroidal array.

3. Amplitude Modulation

Many observed modes have a character of periodic burst with an interval of 1~20 msec. Furthermore, the frequency of some modes is rapidly chirped up and/or down (increased and/or decreased). On the contrary, a few continuous modes are also observed without bursting nature although NBI is continued. The transition from bursting to continuous mode is shown in Fig. 1, where hydrogen beam of energy $E_{NBI} = 155$ keV is tangentially injected into a hydrogen plasma in the configuration of $R_{ax} = 3.6$ m at $B_t = 1.5$ T. The frequency of the lower frequency modes with $m \sim 2/n = 1$ agree well with the TAE gap frequency f_{TAE} (dotted line in Fig. 1) that is formed by $m = 2$ and $m = 3$ mode coupling for $n = 1$ mode. The mode amplitude and the degree of the frequency chirping gradually decrease in time when the energetic ion beta $\langle\beta_{b//}\rangle$ gradually decreases because of the decrease in electron temperature and increase in electron density. That is, the magnetic fluctuation amplitude of TAE decreases from $b_\theta/B_t \sim 3\times10^{-7}$ (burst $t = 0.8$ s) to 1×10^{-7} (continuous $t = 1.2$ s) and saturates. Recently, theoretical [10] and numerical simulation [11] studies point out a possibility that wave trapping of resonant particles would play a key role in controlling the above mentioned non-linear behavior. If the growth time of the wave is comparable to or shorter than slowing down time of energetic ion τ_s, the burst mode will take place. On the other hand, if the growth time of the wave is longer than slowing down

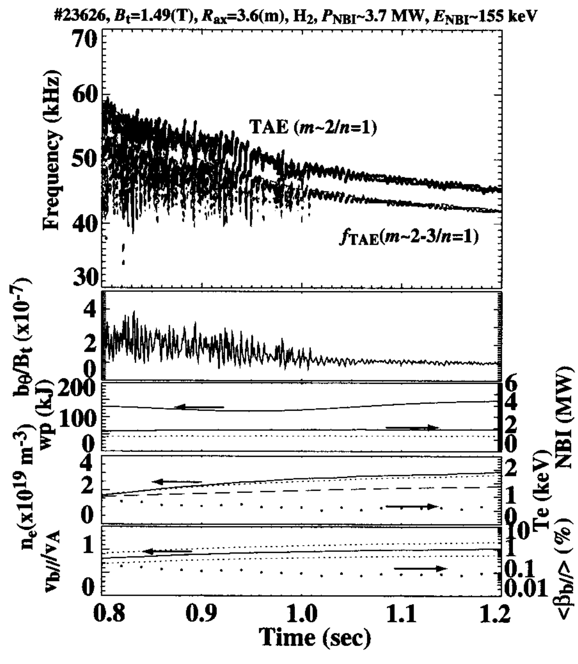

Fig. 1 The transition from bursting to continuous mode at t~1 s is clearly seen. Time evolution of magnetic fluctuation spectrum, magnetic fluctuation amplitude and some plasma parameters.

time of energetic ions, the continuous mode will take place. In our case, however, τ_s is thought to be much longer than the mode growth time. The observed phenomenon might be explained by introduction of the effective collision frequency v_{eff} that is discussed in ref. [12].

We have investigated the excitation conditions, changing the relevant parameters $<\beta_{b//}>$ and $v_{b//}/v_A$, where $<\beta_{b//}>$ and $v_{b//}/v_A$ are the volume averaged energetic ion beta and the ratio of energetic ion velocity to Alfvén velocity. The $<\beta_{b//}>$ is estimated on the assumption of the classical slowing down of energetic ions. The parameter space that the continuous TAEs

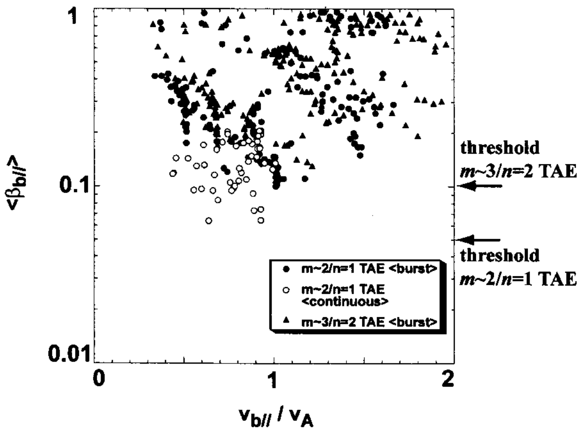

Fig. 2 Excitation conditions of TAEs with m~2/n=1 and m~3/n=2.

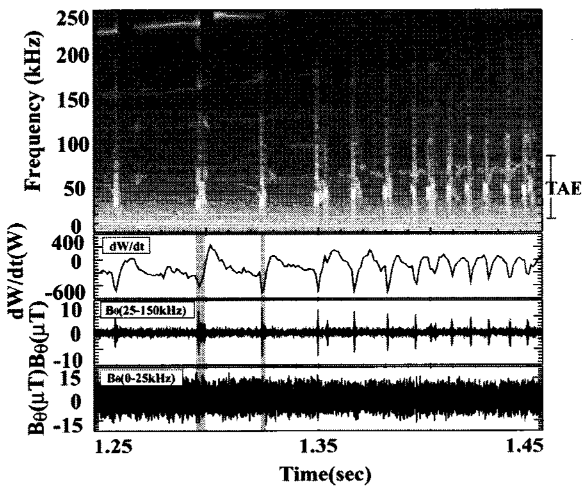

Fig. 3 Time evolution of magnetic fluctuation spectrum, time derivative of the stored energy of the bulk plasma, and filtered magnetic fluctuation amplitude.

with m ~ 2/n = 1 are observed, is shown in Fig. 2. The continuous TAEs are destabilized in the condition of $0.4<v_{b//}/v_A<1$ and $<\beta_{b//}>$ < 2 %. This indicates that the continuous TAEs may be excited via sideband excitation. When the $<\beta_{b//}>$ is greater than 0.2 %, the TAEs become busting. Note that no TAE is detected in the range of $<\beta_{b//}>$ < 0.05 %. The continuous TAEs seem to be excited just above a certain threshold. The TAEs with m ~ 3/n = 2 are always bursting and the excitation threshold seems to be systematically higher than that of TAE with m ~ 2/n = 1. If m ~ 2/n = 1 TAEs are located in the core region. They may have a possibility of core-localization for minimization of continuum damping [13].

The fluctuation amplitude is rapidly increased with the increase in $<\beta_{b//}>$. The relative amplitude of continuous TAE is typically b_θ/B_t ~ 10^{-8}–10^{-7}, and burst TAE is b_θ/B_t ~10^{-7}–10^{-6} at the probe position. When the magnetic shear become low due to the plasma current in the co.-direction and the higher plasma beta at the lower B_t, the drastic TAE bursts can be excited. These modes consist of TAEs with m ~ 3/n = 2 and ~ 1/1 modes. These modes may affect the fast ion transport because the some plasma parameters are simultaneously modulated by TAE bursts, as shown in Fig. 3. In this shot, the calculated $<\beta_{b//}>$ is increased up to 3 % and the amplitude of TAEs reaches up to b_θ/B_t~8×10^{-6}. The transient decrease in the plasma stored energy (dW/dt) suggests that about 15 % of the beam power is lost by each burst. Besides, the signals of E//B neutral particle analyzer suggest that the transport of passing beam particles to the plasma edge is enhanced by these TAE bursts [14]. From these results, we can speculate that these TAEs enhance radial transport of energetic ion before the thermalization. These TAEs gap are located in the plasma edge region (ρ > 0.5). As mentioned above, it is usually hard to destabilize the TAEs in low beta plasma because frequency intersects with the shear Alfvén continua in the edge region. However, the good alignment of the frequency gaps from the plasma core towards the edge can be realized by the decrease in the magnetic shear under low B_t and higher beta.

4. Frequency Chirping

Two kinds of frequency chirping in TAEs and R-TAEs were observed in NBI heated plasma. The time scales of frequency chirping are respectively much smaller than that of plasma equilibrium evolution and comparable to it.

The former is observed with bursting behaviors and

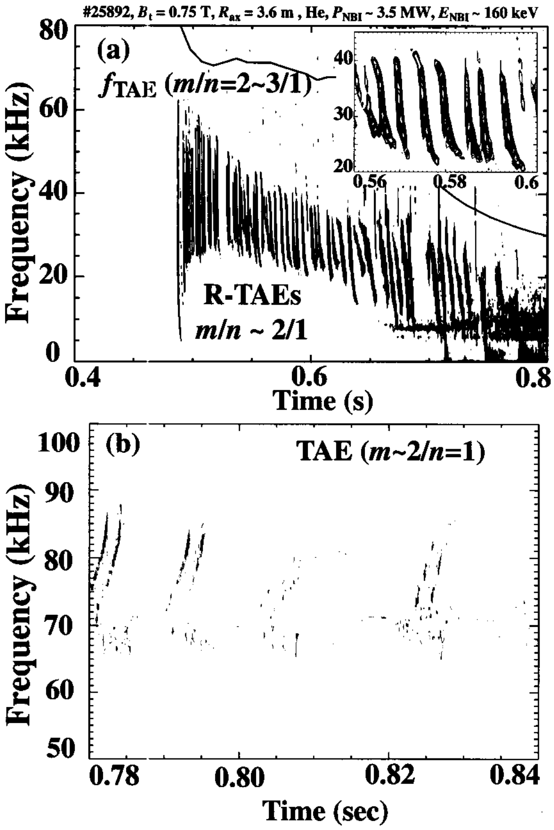

Fig. 4 Time evolution of magnetic fluctuation amplitude and frequency for $m \sim 2/n = 1$ R-TAEs (a) and $m \sim 2/n = 1$ TAEs (b). These modes exhibit rapid frequency chirping.

each burst are repeated every 1~30 ms. The R-TAEs with rapid frequency chirping down were typically observed in the conditions of $B_t < 1$ T and $<\beta_{b//}> > 1$ %, as shown in Fig. 4 (a). Hydrogen beam of energy E_{NBI} = 140 keV is tangentially injected into a Helium plasma in the configuration of R_{ax} = 3.6 m at B_t = 0.75 T. The amplitude of these R-TAEs reaches up to $b_\theta/B_t \sim 10^{-5}$ and by one order of magnitude lager than that of TAE even in the similar plasma conditions. The TAE and R-TAE with rapid frequency chirping upward or downward were sometimes observed with burst duration of 20 ~ 30 ms, as shown figure 4 (b). In this case, the amplitude of these R-TAEs and TAEs are $b_\theta/B_t \sim 10^{-6}$ and $b_\theta/B_t \sim 10^{-7}$, respectively.

The latter is sometimes observed and frequency change will be related to the changes of rotational transport profile, density profile and the ion mass density. The other slow frequency chirping was observed after the ECH was injected. The non-linearity is characterized through the parameter $1/\gamma\tau_s$ [6]. In order to change the energetic ion slowing down time t_s, which is proportional to $T_e^{3/2}$, ECH with P_{ECH} ~ 0.6 MW was injected a low density plasma. The electron temperature increases from 2 keV to 3 keV and density slightly decreases during the ECH injection. The frequencies of observed TAEs and R-TAEs are chirped up during ECH. This phenomenon may be related to the changes of τ_s and n_e profile.

5. Conclusion

Various types of MHD instabilities destabilized by energetic ions are observed in NBI-heated plasmas on LHD. Clear non-linear effects in TAEs and R-TAEs are observed as bursting amplitude modulation and rapidly frequency chirping. Observed modes often exhibit a character of periodic burst. However so-called continuous TAEs without busty nature were sometimes observed on the condition that $<\beta_{b//}>$ is in just above a certain threshold.

When the magnetic shear becomes low due to the plasma current in the co.-direction and the higher plasma beta at lower B_t, the TAEs exhibit a very strong bursting character and rapid frequency chirping. The transient decrease in the plasma stored energy (dW/dt) suggests that about 15 % of the beam power is lost by each burst. These TAEs induce energetic ion transport before the thermalization.

Two kinds of frequency chirping were observed in NBI heated plasma. One is rapid frequency chirping, of which chirping time scale is much shorter than the charactestic time of the plasma equilibrium evolution, and the other is slow frequency chirping variation. Further experimental investigations are required to clarify the correlation between the nonlinear behavior and energetic ion transport.

Acknowledgements

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