Configuration Dependence of Energetic Ion Driven Alfvén Eigenmodes in the Large Helical Device

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Abstract. Energetic ion driven Alfvén eigenmodes (AEs) such as toroidicity-induced AEs (TAEs) and helicity-induced AEs (HAEs) have been observed in neutral beam injection (NBI) heated plasmas of the Large Helical Device (LHD). It is important to clarify the configuration dependence of AEs because the existence and stability of them sensitively depend on the magnetic axis position and plasma beta. These parameters are scanned for the study of the configuration dependence of AEs in LHD. We have studied the energetic ion driven AE in plasmas obtained in three types of magnetic configuration. In order to identify the observed AEs, we have compared between the experimental data and the global mode analysis using CAS3D3. In the configuration with high magnetic shear, two TAEs with m~2/n=1 (m, n: poloidal and toroidal mode number) and m~3/n=2 are typically observed. In the configuration with medium magnetic shear, a number of TAE with n=2~5 are simultaneously observed. In the configuration with low magnetic shear, a number of bursting TAE are observed. We have studied the observed region of AEs in parameter space composed of the resonance and the stability conditions. From these studies of AE using global mode analysis in three-dimensional magnetic configurations, continuum damping of which damping rate depends on the magnetic shear is thought to be an important role in stabilizing AEs in LHD.

1. Introduction

Alfvén eigenmodes (AEs) destabilized by the energetic alpha particles are paid much attention in the physics design of a Deuterium-Tritium (D-T) reactor including the International Thermonuclear Experimental Reactor (ITER) [1]. Energetic alpha particles in a fusion reactor would resonate with MHD modes in course of the slowing down process and destabilize these MHD modes. In turn, the MHD modes would enhance radial transport of alpha particles before thermalization. This would quench fusion burn. Moreover, thus ejected energetic alpha particles might lead to significant damage of the first wall of a fusion reactor. For these reasons, energetic ion driven MHD instabilities such as toroidicity-induced Alfvén eigenmode (TAE) are being extensively studied in many major tokamaks [2] and helical systems [3-5] using energetic ions generated by the neutral beam injection (NBI) and/or ion cyclotron range of frequency heating (ICRH) as well as DT fusion reactions.

Alfvén eigenmodes such as TAEs and helicity-induced AEs (HAEs) [6,7] are observed in NBI heated plasma of the Large Helical Device (LHD) [8-10]. It is important to clarify the configuration dependence of AEs because the existence and stability of them sensitively depend on the radial profiles of the rotational transform $\iota/2\pi$ (=1/q, q: safety factor) and the magnetic shear s (=$\rho dq/[d\rho/q]$). These quantities in low β plasmas of LHD are basically determined by the magnetic axis position of the vacuum field (R_{ax}). The finite plasma β effect and net plasma current I_p can considerably modify these quantities $\iota/2\pi$ and s. In the plasma of R_{ax}=3.6 m, the magnetic shear tends to decrease with the increase in plasma β and finally changes the sign in the central region when averaged β approaches to β~3 %. We have scanned the parameters R_{ax}, β and I_p for the study of the configuration dependence of energetic ion driven AEs in LHD. We present experimental results of AEs observed in LHD and clarify the mode structures through comparison to numerical results by global mode analysis code for three-dimensional (3D) plasmas, CAS3D3 [11].

2. Observation of Alfvén Eigenmodes

We have studied the energetic ion driven AEs in NBI-heated plasma obtained in the following three types of magnetic configuration: (i) low β (<1 %), R_{ax}=3.6 m plasma with high magnetic shear, (ii) low β (<1 %), R_{ax}=3.5 m plasma with medium magnetic shear, and (iii) high β (>2 %), R_{ax}=3.6 m plasma with weak magnetic shear. The radial profiles of ι/2π and s are shown in Fig. 1.

2.1. Configuration (i): High Magnetic Shear (Rax=3.6m, low β)

In the configuration (i), two TAEs with m~2/n=1 (m, n: poloidal and toroidal mode number) and m~3/n=2 are typically observed. A typical discharge in which the TAEs are observed is shown in Fig. 2, where hydrogen beams with the energy of E_{NBI}=150 keV and the power of P_{NBI}~4 MW are tangentially co- and counter-injected into a helium plasma at R_{ax}=3.6 m and magnetic field strength B_t=1.3 T. After t~0.65 s, coherent magnetic fluctuations of which frequencies are scaled with the dependence of $1/(n_e)^{1/2}$ are detected. In this phase, the parallel beam velocity $v_{b//}$ exceeds $v_A/3$ (v_A: Alfvén velocity). A hydrogen ice pellet is injected into the LHD plasma at t~0.8 s, then electron density suddenly increases and coherent magnetic fluctuations are suppressed. The m~2/n=1 mode with the frequency f_{exp}=40~52 kHz (at t=1.6 s) and m~3/n=2 mode with f_{exp}=55~68 kHz (at t=1.6 s) are excited after t~1.1 s. As seen from the calculated TAE gap frequencies ($f_{TAE}=v_A\iota/4\pi R_{ax}$: dotted and broken curves) shown in Fig. 2(a), the observed frequencies of the former mode and the latter mode respectively lie in the n=1 TAE gap formed by m=2 and 3, and n=2 TAE gap formed by m=3 and 4 poloidal mode coupling.

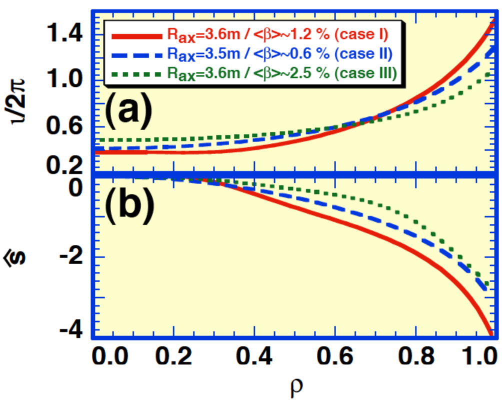

FIG.1. Radial profiles of (a) rotational transform and (b) magnetic shear for the configuration (i), (ii) and (iii).

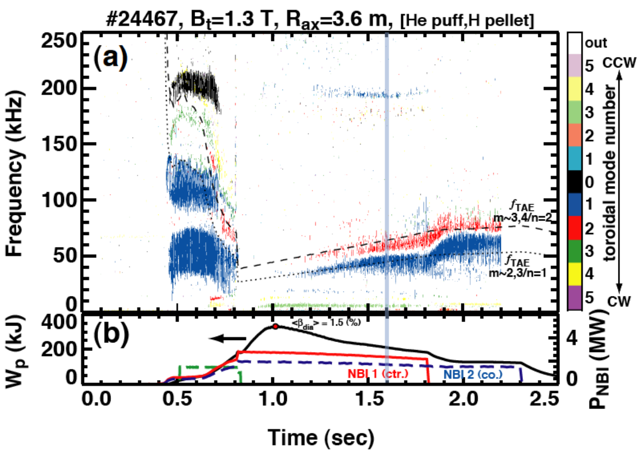

FIG. 2. Typical discharge where TAEs with m~2/n=1 and m~3/n=2 are observed in the plasma of R_{ax}=3.6 m with high magnetic shear (configuration (i)).

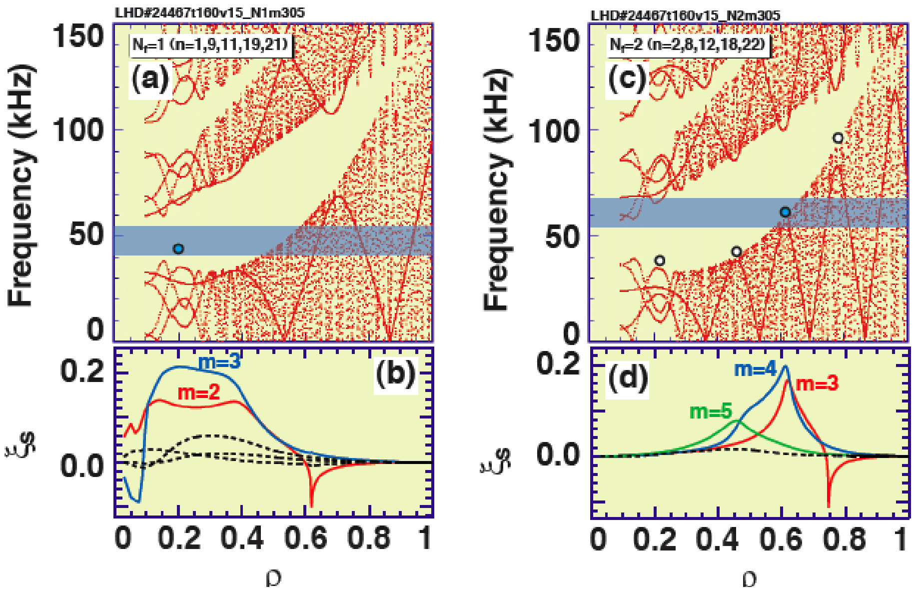

FIG. 3. Shear Alfvén spectra for (a)N_f=1 and (d)N_f=2, and radial profile of discrete mode for (b) n=1 and (d) n=2, of which frequency agree well with that of observed mode.

We compare these observed frequencies at t=1.6 s in the plasma shown in Fig. 2 with the global mode analyses by CAS3D3 that are calculated for 3D magnetic configurations, where toroidal mode coupling is taken into account. The plasma compressibility is ignored (adiabatic index: γ~0) because the plasma β is not so high and shear Alfvén wave dose not couple with sound wave. Shear Alfvén continua in the 3D case are also shown in Fig. 3(a) for N_f=1 and in Fig. 3(c) for N_f=2 (N_f: the number of toroidal mode family), where the toroidal mode coupling among n=±1,±9,±11,±19 and ±21 Fourier modes is taken into account for N_f=1 and n=±2,±8,±12,±18 and ±22 modes for N_f=2. The shaded zone in Figs. 3(a) and (c) indicates the frequency of the observed mode. As seen from Fig. 3(a), the observed mode frequency lies in the innermost n=1 TAE gap, which is formed by m=2 and 3 poloidal mode coupling. The observed frequency intersects with the Alfvén continua with n=1 at the edge of ρ~0.65. The discrete mode of which eigenfunction has a peak at ρ~0.18 is marked by the open circle in Fig. 3(a) and its frequency agrees well with the observed mode frequency. The eigenfunction shown in Fig. 3(b) is basically composed by dominant two poloidal harmonics m=2 and 3, and localized in the plasma core where magnetic shear is quite weak. The m~2/n=1 observed mode indicates a character of a core-localized type TAE (C-TAE) with even parity. The n=1 C-TAE would not suffer from strong continuum damping near the plasma core with very low magnetic shear. The observed frequency of n=1 C-TAE intersects with a lot of Alfvén continua for high-n modes in the outer plasma region ($0.45<\rho<0.65$). However, the n=1 C-TAE would not suffer from continuum damping due to the high-n modes belonging to N_f=1 mode family. Therefore, the continuum damping due to the high-n modes introduced by the toroidal mode coupling is quite weak in LHD as same as CHS [5]. The higher frequency mode (f_{exp}=55~68 kHz) of m~3/n=2 is also analyzed by CAS3D3 code, as shown in Fig. 3(c). The calculated eigenfunction is shown in Fig. 3(d). As seen from these figures, the discrete mode mainly consists of three Fourier components with m=3,4 and 5, and intersect with the n=2 shear Alfvén continuum at the ρ~0.75. The eigenfunction of the observed m~3/n=2 mode extends radially from the gap toward central region with low magnetic shear. This mode exhibits a feature of global type TAE (G-TAE) and is different from the character of the observed n=1 C-TAE.

2.2. Configuration (ii): Medium Magnetic Shear (Rax=3.5, low β)

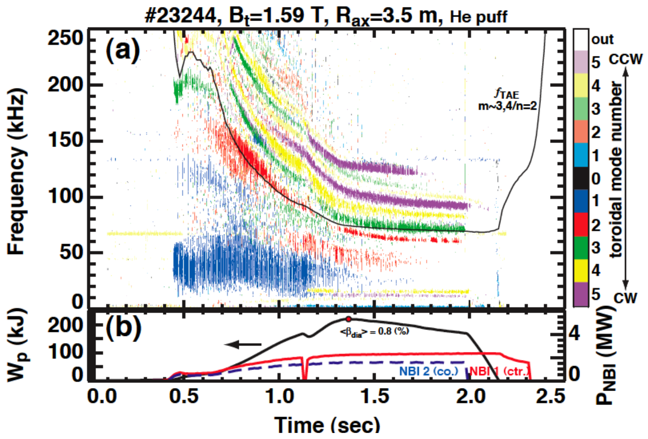

FIG. 4. Typical discharge where a number of TAEs are simultaneously observed in the plasma of R_{ax}=3.5 m with medium magnetic shear (case (ii)).

In the configuration (ii), of which magnetic shear is smaller than that of R_{ax}=3.6 m (configuration (i)), a number of TAE with n=2~5 are simultaneously observed, as shown in Fig. 4. These modes in the frequency range of 50 kHz to 250 kHz are excited in the time window of $v_{b//}>v_A/3$, having the mode numbers of m~3/n=2,~4/3,~5/4 and ~6/5. The frequency separation between neighboring modes is explained not by the effect of Doppler shift due to the toroidal plasma rotation, but by the TAE gap location of each modes. The calculated shear Alfvén continua with N_f=2 and 5 at t=1.5 s are shown in Figs. 5(a) and (c). The shaded zones in Fig. 5 indicate the observed frequencies of the mode f_{exp}=64~67 with m~3/n=2, and 98~102 kHz with m~6/n=5, respectively. A lot of discrete modes are found in respective TAE gaps and the peak of each eigenfunction is represented by the solid circle in the Figs. 5(a) and (c). The calculated eigenfunctions for observed mode with n=2 and 5 are shown in the Figs. 5(b) and (d). In contrast with the m~3/n=2 TAE observed in the configuration (i) (Figs. 3(d)), the TAE with n=2 shown in Fig. 5(b) consists of two dominant Fourier components m=3 and 4. This has a feature of "gap localized TAE" [10]. The TAEs with n=5 shown in Fig. 5(d) consist of some poloidal components and localize around the TAE gap in the plasma outer region (ρ>0.6). The observed mode of f_{exp}=98~102 kHz with n=5 would be EAEs existing in the

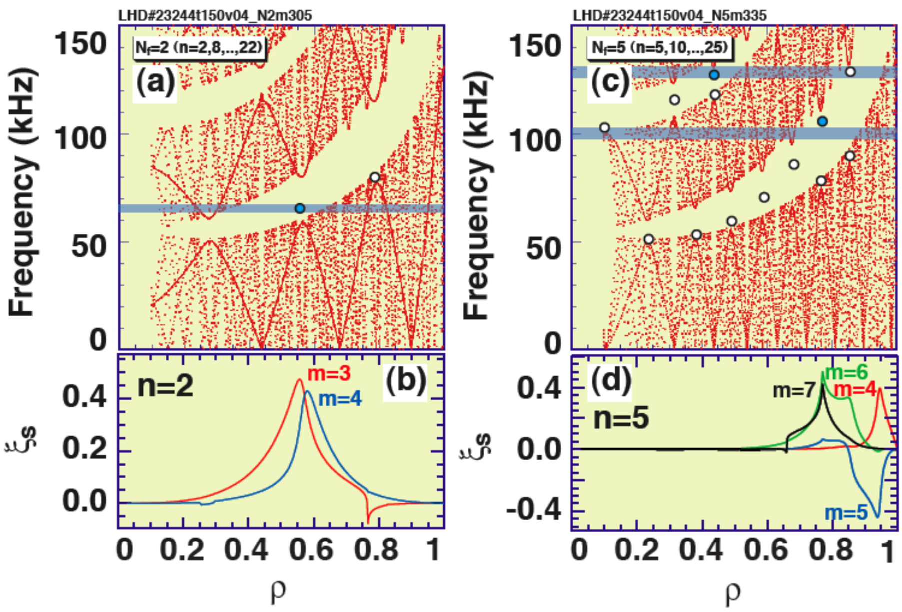

FIG. 5. Shear Alfvén spectra for (a) N_f=2 and (d) N_f=5, and radial profile of discrete mode for (b) n=2 and (d) n=5, of which frequency agree well with that of observed mode.

plasma core region (ρ~0.1). However, the dominant m number of observed modes (m~6/n=5) does not agree with that of EAE. In conclusion, the observed modes with n=5 are thought to be TAEs existing in the outer region of ρ > 0.6. On the other hand, the observed highest frequency mode of f_{exp}~129 kHz is thought to be n=5 EAE of which gap locates at ρ~0.4.

2.3. Configuration (iii): Low Magnetic Shear (Rax=3.6 m, high β)

In the configuration (iii), of which magnetic shear is further reduced from the core to the plasma peripheral region due to increased β even in the configuration of R_{ax}=3.6 m, a number of bursting TAE are observed, as shown in Fig. 6. It is noted that bursting TAE appreciably affect the energetic ion transport and/or bulk plasma confinement because some plasma parameters, such as plasma stored energy W_p and H_α, are simultaneously modulated with bursting TAEs. The calculated shear Alfvén continuum with N_f=2 at t=1.4 s and the eigenfunction of the discrete mode are shown in Figs. 7(a) and (b), respectively. The TAE gaps are well aligned from the plasma core to the edge with fairly large gap width because of low magnetic shear and large Shafranov shift due to the finite β effect. The CAS3D3 analysis has demonstrated that the eigenfunction of TAE is widely extended from the core to the edge, clearly exhibiting G-TAE character (Fig. 7(b)). Accordingly, the G-TAE having bursting characteristics is strongly excited because of high pressure gradient region of energetic ions moves toward the edge and the growth rate of the mode will overcome continuum damping.

Beside the observation of TAEs, high frequency mode with n=2, of which frequency is about eight times higher than that of TAE gap, are newly observed in the plasma shown in Fig. 6. The coherent modes in the range of 180<f_{exp}<220 kHz are observed after t=1 s. The observed modes are identified to be n=2 and propagate in the diamagnetic drift direction of energetic ions. These modes are thought to be Alfvén eigenmodes, because the frequencies of these

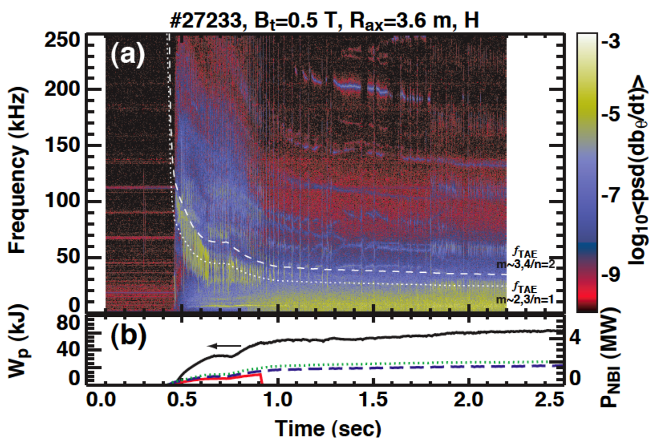

FIG. 6. Typical discharge where a number of bursting TAEs and a HAE are simultaneously observed in the high β plasma of Rax=3.6 m with low magnetic shear (case (iii)).

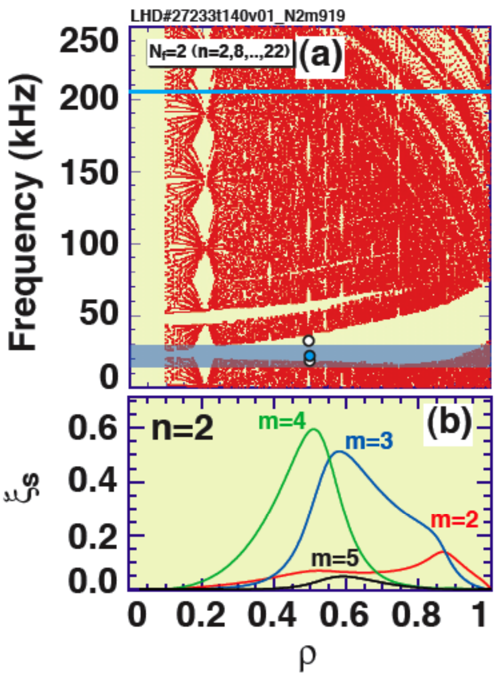

FIG. 7. Shear Alfvén spectra for (a) Nf=2 and radial profile of discrete mode for n=2 of which frequency agree well with that of observed mode. The observed frequency of HAE is also shown by blue solid line.

modes are proportional to the Alfvén velocity v_A. The toroidal mode coupling related to 3D magnetic configuration leads to a generation of new spectral gap, which is related to the helical fields components. In this new gap, the HAEs can be excited by the energetic ions. We compare these observed frequencies at t=1.4 s of the plasma shown in Fig. 6 with the shear Alfvén spectrum for N_f=2 as shown in Fig. 7. The HAE gap has a good alignment from the plasma core toward the edge. The continua with high-n mode exist in HAE gap and the new continua inside HAE gap might be produced by the absence of helical symmetry of helical field components. The former continua may not affect the low-n modes because the toroidal mode coupling is weak and the latter continua may affect the low-n modes. The solid line in Fig. 7 indicates the measured frequency of magnetic fluctuation. The frequency lies in the HAE gap at the plasma edge (ρ~0.8) and intersects newly generated continua inside the HAE gap location. We predict that the modes would be excited in despite of the suffering of continua damping. The pressure profile of energetic ions is predicted to be flat because the Larmor radius of passing energetic ion reaches up to 10 % of plasma radius. Therefore, the pressure gradient of energetic ion has a peak near the plasma edge and the growth rate of the mode may be significantly large enough to overcome the damping. It is concluded from these analyses that the observed high frequency modes are thought to be HAEs.

3. Parametric Study for AEs

MHD instabilities will be destabilized by the energetic ions when a certain threshold conditions are satisfied. As regard to the AEs, the linear growth rate being proportional to the pressure gradient of energetic ions must be large enough to overcome the damping rate of the waves. This condition may be translated to the condition for the averaged beam beta $\langle\beta_{b//}\rangle$. Moreover, the velocity of energetic ions $v_{b//}$ is required to satisfy the resonance condition with the Alfvén wave. The TAE resonance condition for the fundamental excitation is $v_{b//}/v_A>1$ and sideband excitation via the drift modulation of energetic ion orbit is $v_{b//}/v_A>1/3$. We have investigated the excitation conditions of TAE and HAE in the parameter space of $\langle\beta_{b//}\rangle$ and $v_{b//}/v_A$ in the configurations of R_{ax}=3.6 m and 3.5 m, changing various plasma parameters $\langle n_e\rangle$, B_t, P_{NBI}, and ion species (H/He). As shown in Fig. 8 for TAEs and Fig. 9 for HAEs, the parameters are scanned over wider range of $\langle\beta_{b//}\rangle\leq10$ % and $v_{b//}/v_A\leq4$, compared with that in major tokamaks, W7-AS and CHS. It is clearly seen from Fig. 8 that the TAEs with m~3/n=2

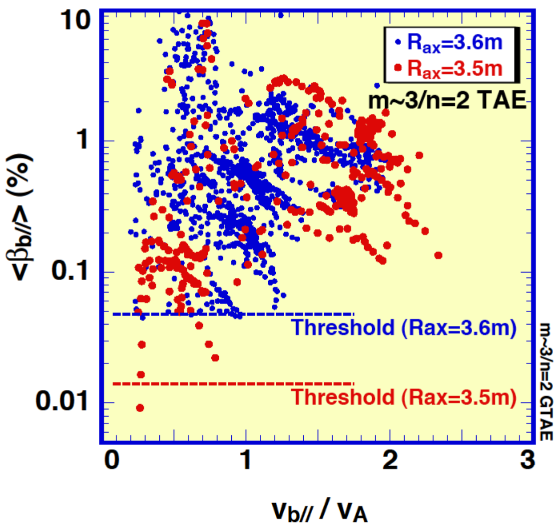

FIG. 8. Excitation region for m~3/n=2 G-TAEs in configuration of the R_{ax}=3.6 m (blue circle) and 3.5 m (red circle).

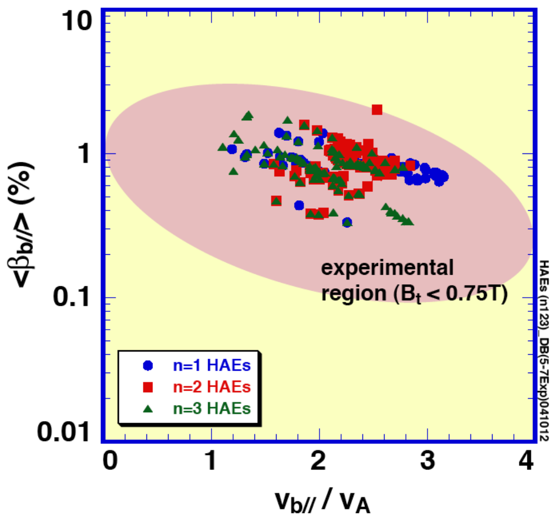

FIG. 9. Excitation region for HAEs with n=1,2,3 in configuration of the R_{ax}=3.6m and B_t >0.75 T.

are destabilized in the condition of $0.3<v_{b//}/v_A<2.0$ and $<\beta_{b//}>>0.05$ % for R_{ax}=3.6 m plasma (configuration (i) and (iii)), and $0.3<v_{b//}/v_A<2.3$ and $<\beta_{b//}>>0.01$ % for R_{ax}=3.5 m plasma (configuration (ii)), respectively. This indicates that the TAEs are excited via sideband excitation ($v_{b//}/v_A>1/3$) as well as fundamental excitation ($v_{b//}/v_A>1$). TAEs are not observed in the region of $v_{b//}/v_A>2.3$ that corresponds to higher electron density. This result may be explained by fewer amounts of resonant energetic ions to destabilize TAEs against various damping mechanisms. The difference in the excitation threshold of m~3/n=2 G-TAEs in the R_{ax}=3.5 m and R_{ax}=3.6 m plasmas seems to be related to the difference of the damping rate. The m~3/n=2 G-TAEs would suffer from continuum damping, of which damping rate depends on the magnetic shear near the plasma edge. It is speculated that the damping rate of continuum damping of m~3/n=2 G-TAEs in the R_{ax}=3.6 m plasmas are higher than that in the R_{ax}=3.5 m plasmas, because the magnetic shear at edge of R_{ax}=3.6 m plasma is larger than that in R_{ax}=3.5 m plasma. The HAEs are only observed in the configuration of R_{ax}=3.6 m and $\beta\geq2$ %. The HAEs with n=1~3 are destabilized in the range of $<\beta_{b//}>\geq$ 0.4 % and $1\leq v_{b//}/v_A\leq3.2$. This range of $v_{b//}/v_A$ is consistent with the fundamental excitation of HAE with n=1~3.

4. Summary

In NBI-heated LHD plasmas, various Alfvén eigenmodes destabilized by the energetic ions have been observed. The configuration dependence of AEs has been investigated for typical three configurations with high, medium and low magnetic shear. The frequencies of observed AEs agree well with the results from global mode analysis code CAS3D3 for three-dimensional plasmas. For the observed AEs, the eigenfunctions are also calculated by the code. The characteristic feature of these observed TAEs are identified, that is, core localized TAE (C-TAE), global TAE (G-TAE) and gap-localized TAE. Moreover, a new AE, that is, HAE has been observed for the first time in a certain condition. We have studied the excitation condition of G-TAEs in the configuration of R_{ax}=3.5 m and R_{ax}=3.6 m. These studies of AEs excitation in three magnetic configurations of LHD suggest that continuum damping plays an important role in stabilizing AEs.

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