Possibility of excitation of Alfvén eigenmodes by energetic ions near the plasma edge in the Compact Helical System

Takafumi ITO[1)], Kazuo TOI, Go MATSUNAGA[2)], Mitsutaka ISOBE,
Tsuyoshi AKIYAMA, Takashi MINAMI, Kenichi NAGAOKA and CHS Experimental Group

National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan

[1)]Department of Energy Engineering and Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya City, Aichi 464-8601, Japan

[2)]Japan Atomic Energy Agency, 801-1 Mukouyama, Naka, Ibaraki 311-0193, Japan

(Received: 4 September 2008 / Accepted: 5 February 2009)

Energetic ion driven MHD modes are surveyed over the wide range of line averaged electron density from ~0.3 to ~5×10^{19} m^{-3} in neutral beam injection (NBI) heated inward-shifted plasmas of the Compact Helical System (CHS). Toroidicity-induced Alfvén eigenmodes (TAEs) with m~2(m=2+3)/n=1, m~3(m=3+4)/n=2, m~4(m=4+5)/n=2, m~4(m=4+5)/n=3, and m~5(m=5+6)/n=3 are identified. Global Alfvén eigenmode with m~3/n=1 is also excited near the plasma center by energetic ions. TAEs of which gap locates in the outer region of ρ>0.8 are never excited by NBI. In the edge region, TAEs are very stable because of less energetic ion drive and large damping rates that would mainly come from continuum damping in the edge with high magnetic shear.

Keywords: Alfvén eigenmodes, energetic ion driven modes, MHD instability, continuum damping, helical plasma

1. Introduction

Energetic ion driven MHD instabilities and their effects on energetic ion transport are being investigated in many tokamaks and helical devices toward the burning plasma condition[1]. Especially, the most harmful MHD modes are thought to be toroidicity-induced Alfvén eigenmodes (TAEs), because they are very weak damping rate due to less continuum damping. Thus strongly destabilized TAEs may enhance transport and/or loss of energetic ions.

The stability of TAEs can be evaluated using the effective growth rate γ. It may be expressed as a difference between the driving rate (or growth rate) by energetic ions γ_{drv} and the damping rate γ_{damp} :

$$\gamma = \gamma_{drv} - \gamma_{damp} \qquad (1)$$

For simplicity, the linear growth late is often adopted as γ_{drv}. This is analytically expressed as[2]:

$$\frac{\gamma}{\omega_0} \approx \frac{9}{4}\left[\beta_\alpha\left(\frac{\omega_{*\alpha}}{\omega_0} - 1/2\right)F\left(\frac{v_A}{v_\alpha}\right)\right] \qquad (2)$$

Here ,the quantities ω_0, $\omega_{*\alpha}$, β_α, F, v_A and v_α are respectively the angular eigenfrequency of the mode, the drift frequency of energetic ions, the toroidal beta of energetic ions, the fraction of resonant energetic particles, Alfvén speed and energetic ion velocity. The driving rate increases with the increase in β_α, $\omega_{*\alpha}$ and $F(v_A/v_\alpha)$. In the neutral beam injection (NBI) heated plasma, the driving rate will depend on the injection power and the radial profile of the beam deposition. On the other hand, the damping rates γ_{damp} will sensitively be affected by the magnetic shear and the rotational transform in addition to plasma temperature and density.

In the Compact Helical System(CHS), experimental results on the wide aspects of TAEs, the other AEs and energetic particle modes (EPMs) were provided by previous studies[3-5]. In this paper, we discuss what radial locations TAEs are excited by NBI in a specific magnetic configuration of CHS where good confinement of energetic ions is expected.

2. Experimental Setup and Typical NBI heated plasmas

ito.takafumi@LHD.nifs.ac.jp

CHS is a heliotron/torsatron device which has a poloidal polarity number *l*=2, toroidal period number N=8, the major radius R~1 m, and the averaged minor radius <a>~0.2 m. A typical discharge initiated by ECH is heated up by NBI heating in a configuration of the magnetic axis position in the vacuum field R_{ax}=0.921m at B_t=0.9T, as shown in Fig. 1. Two tangential beam lines of NBI of which acceleration energy of 40keV and 36keV are employed as co-injection. The total absorbed power is about 1.7MW. Electron density is controlled by puffing of hydrogen gas. In a relatively low density plasma as shown in Figs.1(b) and (c), appreciable plasma current is induced by intense neutral beam injection to the co-direction, which tends to raise the rotational transform in the core region.

Coherent magnetic fluctuations are often observed in these discharges. The time evolution of their frequency spectra is shown in Figs. 1(e)–(g), for the shots #231294, #231294 and #236303. The frequency range of these MHD modes corresponds to the TAE frequency $f_{TAE}=v_A/(4\pi q^* R)$ where $q^*=(2m+1)/2n$ (m and n: poloidal and toroidal mode numbers) or that of energetic particle mode (EPM). Moreover, these coherent modes are clearly excited during NBI phase, which also suggests that these MHD modes will be energetic ion driven modes. In the case of extremely low electron density such as Fig.1(e), EPM having the frequency considerably lower than f_{TAE} exhibits strong bursting character and frequency chirping, for example, in the phase from 0.05s to 0.085s. On the other hand, in the higher density case shown in Fig.1(f), the bursting EPMs are completely suppressed except the initial phase of NBI and the coherent fluctuations in the frequency range from ~20kHz to ~50kHz becomes visible. It should be noted that fluctuations in higher than 100kHz disappeared in this higher density case.

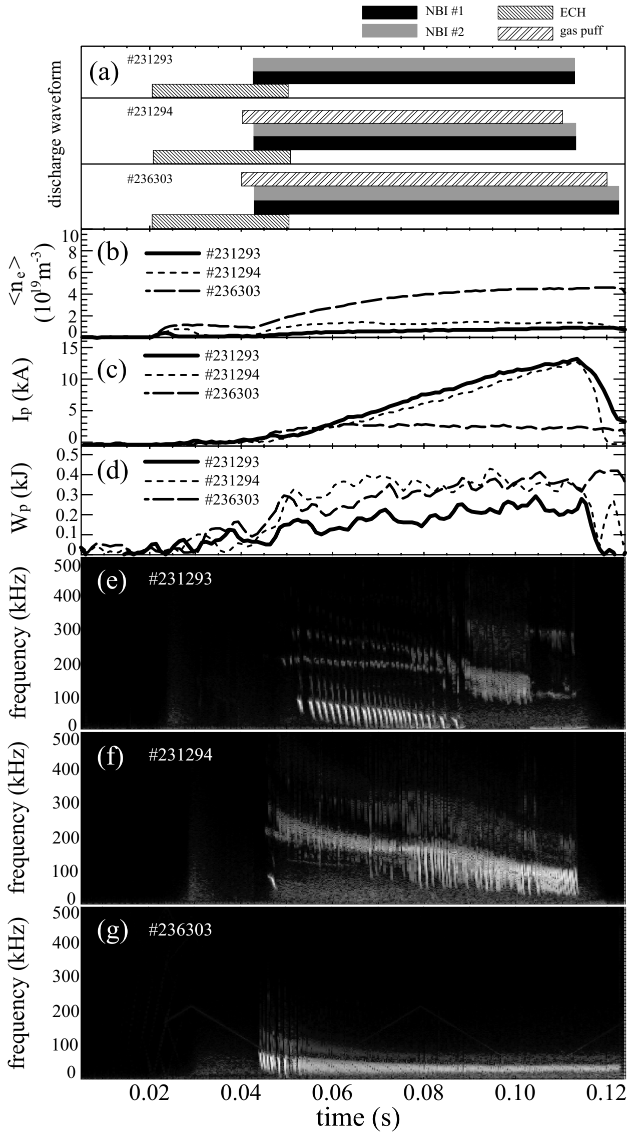

Fig. 1. The typical waveforms of NBI heated plasmas in CHS. (a) time diagram of heating and gas fueling. (b) line averaged electron density measured by the FIR interferometer. (c) plasma current. (d) stored plasma energy. Fourier spectrograms of (e), (f) and (g) are from magnetic probe signal in each of these discharges.

3. Observation of Energetic Ion Driven Alfvén Eigenmodes

Figure 2 summarizes the frequency and amplitude of these coherent MHD modes observed in NBI heated plasmas of CHS, as a function of line averaged electron density. The mode numbers m and n were successfully identified by poloidal and toroidal arrays of magnetic probes as (~2, 1), (~3, 1), (~3, 2), (~4, 2), (~4, 3) and (~5, 3). The dependence of the mode frequency on the line averaged electron density $<n_e>$ follows the density dependence in f_{TAE} and the frequency is close to f_{TAE} which is evaluated using $<n_e>$, as seen from Fig.2. In the estimation of f_{TAE}, we assumed Z_{eff} = 3 and fully ionized carbon C^{6+} as main impurity from the past data on Z_{eff} and impurities in CHS [6,7].

It should be note that the mode (m, n)=(~3, 1) is thought to be GAE when the relevant TAE gap is not formed because the rotational transform $\iota/2\pi$ in the plasma core region is larger than the value of n=1, m=3+4 gap, i.e., $\iota/2\pi = 2n/(2m+1) = 2/7$ in the R_{ax} = 0.921m configuration. For the GAE, the GAE frequency estimated at the plasma center as $f_{GAE} = (|k_{//}|v_A)_{\rho=0}/2\pi$ is shown with the dotted curve in Fig.2(b). Even though a small amount of plasma current is induced in the co-direction, the above-mentioned gap is never produced because the rational surface of m=3/n=1 moves inward.

Shear Alfvén spectra for observed toroidal mode numbers n=1, n=2 and n=3 are shown in Fig.3, where the rotational transform profile is calculated using experimental data as a net current free plasma. Here, ion density profile of $n_i/n_i(0)=1-0.9\rho^2$ (ρ: normalized minor radius) with the experiment data $<n_e>$ and C^{6+} concentration corresponding to $Z_{eff}=3$ are assumed. The observed modes (~2, 1), (~3, 2), (~4, 2), (~4, 3) and (~5, 3) correspond to TAE modes for the spectral gap formed by mode coupling of m=2 and m=3 (m=2+3) / n=1, m=3+4/n=2, m=4+5/n=2, m=4+5/n=3 and m=5+6/n=3, respectively. Each gap position is marked with **a**, and **c–f** in Fig.3, for Figs.2(a), 2(c) to 2(f). These positions are located at ρ~0.5, ρ~0.7, ρ~0.55, ρ~0.7 and ρ~0.8, respectively. The m=3/n=1 GAE is located just above the shear Alfvén continuum for m=3/n=1 and is marked with **b**, and is at ρ ≤ 0.1. The Alfvén spectra are calculated without net plasma current, as mentioned above. Even if net plasma current up to ~13 kA flows in co-direction as observed in discharges shown in Figs. 1 and 2, it is inferred that these gaps will move inward by about δρ~0.1 or less,.

The common feature seen from Fig.2 is that the magnetic fluctuations tend to increase with the increase in line averaged electron density till $<n_e>\sim1.5\times10^{19}$ m^{-3}. This may be interpreted that NBI power deposition is not large enough in such lower density due to appreciable shine-through of NBI[8]. On the other hand, in the high density range more than 3×10^{19} m^{-3}, the TAE modes such as m~4/n=3 , which are located in the outer region of ρ ≥ 0.7 (Fig.3) are completely suppressed or have very low amplitude less than noise level because of reduced energetic ions.

In these experimental conditions, various damping mechanisms may play a role in excitation of observed TAEs, for instance, the continuum damping, radiative damping, and bulk electron Landau damping.

The most significant effect on suppression of TAEs in higher density will be attributed to the decrease in energetic ion pressure which is in proportion to the product of slowing down time of the beams and absorbed NBI power, and appreciable damping rates by continuum and/or radiative damping mechanism related to the magnetic field structure. On the other hand, TAEs and EPMs tend to be unstable because of sufficiently high beam pressure in the lower density plasmas. The above mention speculation is qualitatively supported by the data shown in Fig.2.

The fluctuation levels of m=3, n=1 GAE and m~4/n=2 TAE are almost independent of line averaged electron density in the range from $\sim1.5\times10^{19}$ m^{-3} up to $\sim5\times10^{19}$ m^{-3}. This fact may be explained by that NBI deposition is increased with the increase in <ne> and beam pressure in the plasma core is still kept at a certain level to destabilize these modes because of high central electron temperature.

4. Summary

In NBI heated CHS plasmas, energetic-ion-driven Alfvén eigenmodes are searched in the wide range of line

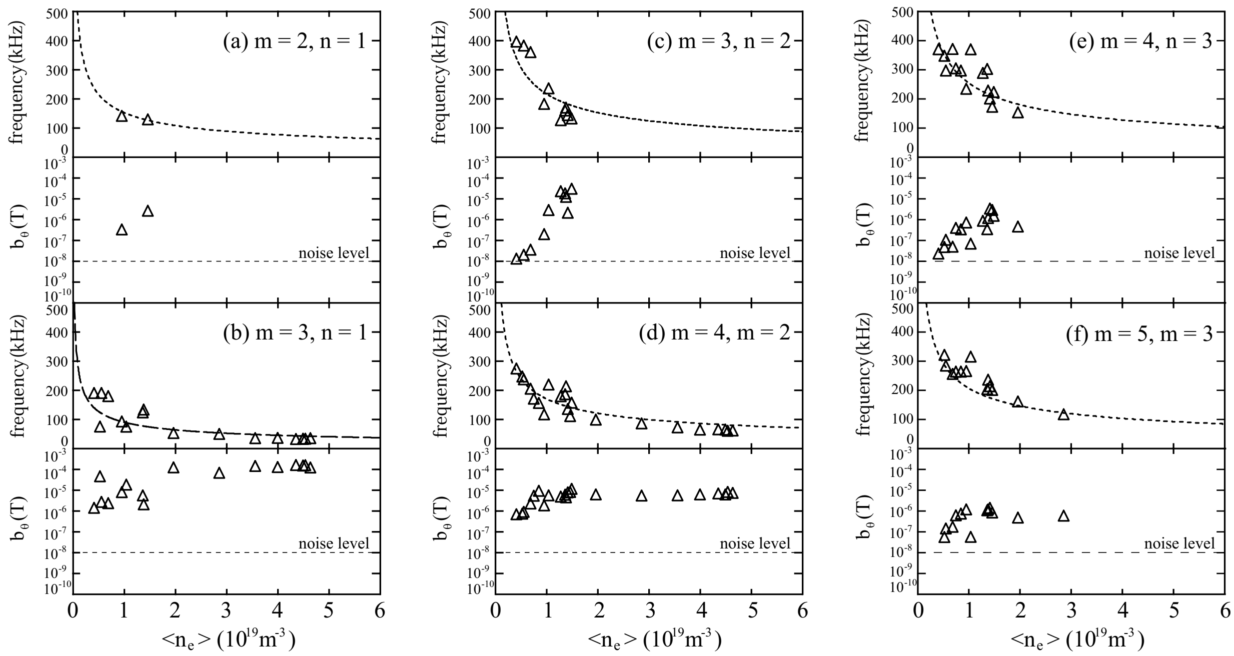

Fig.2 Frequency and the amplitude of magnetic fluctuations of TAEs and GAE as a function of line averaged electron density. The dotted curves in Fig.2(a)–(f) except Fig.2(b) indicate the TAE gap frequency f_{TAE} of which gap is formed by coupling between m and m+1 at n. The dotted curve in Fig.2(b) indicates the GAE frequency evaluated at the plasma center as $f_{GAE}=(|k_{//}|v_A)_{\rho=0}/2\pi$. Here, f_{TAE} and f_{GAE} are calculated using $<n_e>$ on the assumption of Z_{eff} = 3 having fully ionized carbon impurity for hydrogen plasmas at B_t=0.9T. Dashed line in (b) indicates GAE frequency which is roughly estimated by the parameters in the plasma core region.

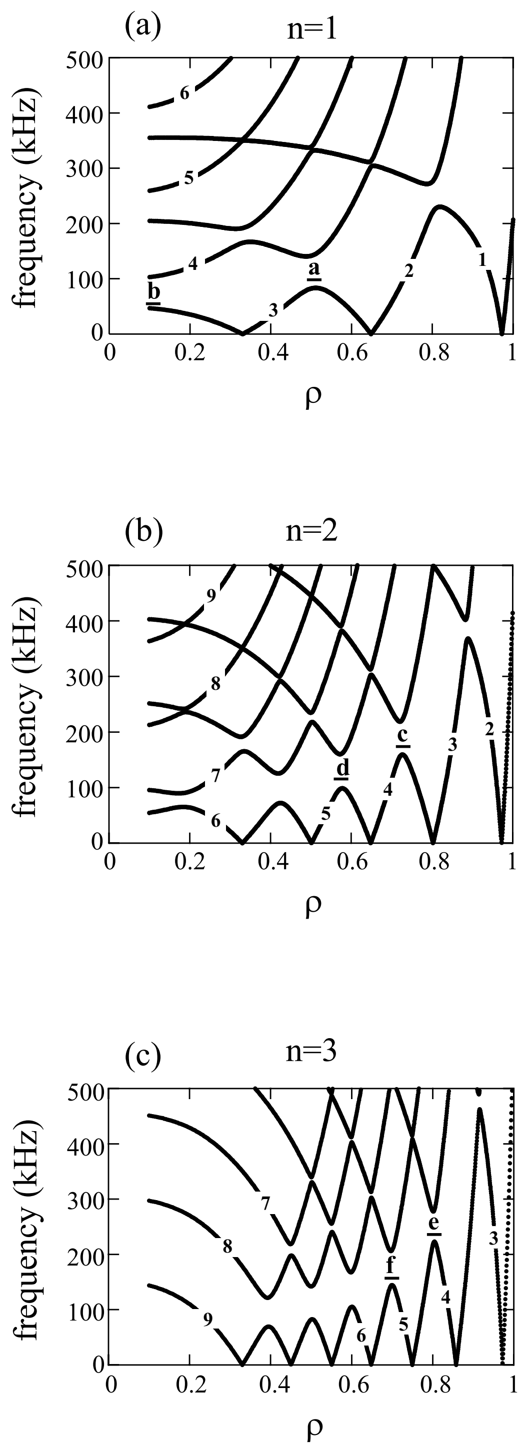

Fig.3 Shear Alfvén spectra calculated for (a) n=1, (b) n=2 and (c) n=3 in the magnetic configuration of R_{ax}=0.921m, where averaged toroidal beta is 0.5%, line averaged electron density $\langle n_e \rangle = 3\times10^{19}$ m^{-3} and the toroidal magnetic field B_t = 0.9T. In this calculation, no net plasma current is assumed. Each poroidal mode number m is numbered on their solid curves. The labels (**a**, **c**–**f**) show the TAE gaps for observed modes shown in Fig.2. The label (**b**) shows the mode location of GAE observed.

averaged electron density from 0.3 to 4.8×10^{19} m^{-3}. Various TAEs and GAE were identified. The gap locations of these modes are at ρ= 0.5~0.8. It should be noted that no TAE of which gap is located near the plasma edge of ρ> 0.8 was observed. It is thought to be very weak energetic ion drive near the plasma edge region in the configuration of R_{ax}=0.921m. On the other hand, TAEs excited in the plasma edge by application of alternating magnetic field perturbations exhibited large damping rate [9]. Clear suppression of TAEs located in ρ > 0.7 in the relatively high density of $\langle n_e \rangle > 3\times10^{19}$ m^{-3} can be consistently explained by the above facts. Large damping rate for TAEs in the plasma edge region of CHS is thought to be large continuum damping because of high magnetic shear there.

5. References

[1] A. Fasoli *et al.*, Nucl. Fusion **47**, S264 (2007).
[2] G.Y. Fu and J.W. Van Dam, Phys. Fluids **B1**, 1947 (1989).
[3] K. Toi *et al.*, Nucl. Fusion **40**, 1349 (2007).
[4] M. Isobe *et al.*, Nucl. Fusion **46**, S918 (2006).
[5] G. Matsunaga *et al.*, Phys. Rev. Lett. **94**, 225005(2005)
[6] S. Morita *et al.*, . Fusion Eng. Des. **34–35**, 211(1997)
[7] S. Morita (private communication)
[8] K. Matsuoka *et al.*, Plasma Phys. Control. Fusion **34**, 1909(1992)
[9] T. Ito *et al.*, Plasma Fusion Res. **3** 033(2008)