GLOBAL MHD MODES EXCITED BY ENERGETIC IONS IN HELITRON/TORSATRON PLASMAS

K. TOI, M. TAKECHI1), S. TAKAGI1), G. MATSUNAGA1), M. ISOBE,
T. KONDO2), M. SASAO, D.S. DARROW3), K. OHKUNI1), S. OHDACHI,
R. AKIYAMA, A. FUJISAWA, M. GOTOH, H. IDEI, K. IDA,
H. IGUCHI, S. KADO, M. KOJIMA, S. KUBO, S. LEE, K. MATSUOKA,
T. MINAMI, S. MORITA, N. NIKAI1), S. NISHIMURA, S. OKAMURA,
M. OSAKABE, A. SHIMIZU1), Y. SHIRAI2), C. TAKAHASHI,
K. TANAKA, T. WATARI, Y. YOSHIMURA

National Institute for Fusion Science, Toki-shi 509-5292, Japan
1) Dep. Energy Eng. Science, Nagoya Univ., Nagoya 464-8603, Japan
2) The Graduate Univ. for Advanced Studies, Toki-shi, 509-5292, Japan
3) Princeton Plasma Physics Laboratory, Princeton, N.J., U.S.A.

Abstract

In the CHS heliotron/torsatron, fishbone instabilities(FBs) and toroidal Alfven eigenmodes(TAEs) are observed for the first time, in NBI heated plasmas where small beam driven current is induced. Pulsed increase in energetic ion loss flux is detected by an escaping ion probe during the m=3/n=2 FBs(m,n : poloidal and toroidal mode numbers). The sawtooth crash is often induced by the m=2/n=1 FBs. The current driven internal kink mode and pressure driven interchange modes are thought to be relevant MHD instabilities to FBs. TAEs with n=1 and n=2 are identified, and localized near the plasma core region where fairly low magnetic shear would be realized by the small net plasma current. So far, the observed TAEs do not lead to enhanced loss of energetic ions because of low magnetic fluctuation level.

1. INTRODUCTION

Fishbone instabilities[1] and Alfven eigenmodes[2] driven by the presence of energetic ions are observed in a tokamak plasma heated by intense neutral beam and/or ICRF heating, and often lead to enhanced loss of energetic ions before their thermalization. In a tokamak fusion reactor, these kinetically driven modes, in particular, toroidal Alfven eigenmodes(TAEs) might be excited by energetic alpha particles and considerably degrade their confinement[3,4]. Therefore, excitation and suppression of TAEs is intensively studied in large tokamaks. This issue is also very important for helical systems[5]. In particular, energetic ion loss might be considerably enhanced by these MHD modes in a helical system with appreciable magnetic field ripple. Recently, we observed fishbone instabilities(FBs) [6] and toroidal Alfven eigenmodes(TAEs) [7] excited by energetic ions in the CHS heliotron/torsatron[8]. FBs in a tokamak plasma are excited by resonant interaction of m=1/n=1internal kink mode with the precessional motion of trapped ions. In contrast to the tokamak plasma, the CHS plasma is basically current-free and is confined in the three dimensional magnetic configuration. Therefore, main purpose of this research is to clarify the relevant MHD mode and the resonant orbit of energetic ions. On the other hand, TAEs can be destabilized by resonant interaction of Alfven waves with circulating motion of passing ions or bounce motion of trapped ions in the troidicity induced Alfven spectrum gap. In a tokamak, the radial variation of the TAE frequency $f_{TAE}=V_A/(4\pi Rq)$ is fairly small (V_A: Alfven velocity, q: safety factor), and then continuum damping of TAEs near the plasma edge might not act efficiently. On the other hand, the TAE frequency in CHS rapidly increases towards the edge, because q decreases towards the edge. This means that strong continuum damping of TAEs could take place near the edge. However, TAEs are obviously excited on the certain experimental conditions of CHS. In this paper we describe characteristics of FBs and TAEs observed in CHS. In these experiments, the electron density is kept low ($\leq 3\times10^{19}\text{m}^{-3}$) to enlarge contribution of energetic ions to the bulk plasma. Typically, averaged (parallel) beta of energetic beam ions is in ~ 0.1-0.3 % and is comparable to the bulk plasma beta. Neutral beams are injected nearly parallel to the toroidal field and induce appreciable net plasma current dominated by beam driven current.

2. FISHBONE INSTABILITIES

Characteristics of FBs depend upon the position of magnetic axis in the vacuum field (Rax), where the plasma of Rax≤0.92m is referred as the "inward-shifted" plasma and the one of Rax≥0.95m as the "outward-shifted" one. In the outward-shifted plasmas, m=3/n=2 FBs are observed. In the inward-shifted plasmas, m=2/n=1 FBs are observed.

Figure 1(a) shows time evolution of magnetic fluctuations of m=3/n=2 FBs and energetic ion loss flux measured by an escaping ion probe(EIP)[9], where Rax=0.95 m. As seen from Fig.1(a), magnetic fluctuations exhibit the fishbone like amplitude modulation during the NBI pulse. Energetic ion loss is transiently enhanced by FB-burst. Figure 1(b) shows the expanded time trace of magnetic fluctuations and energetic ion loss flux shown in Fig.1(a). The ion loss is suddenly enhanced when the magnetic fluctuations reach the peak level. Recently, it has been clarified that energetic ions with the pitch angle near 90˚ are preferentially expelled by m=3/n=2 FBs, in addition to the loss flux with the pitch angle around 45˚[9]. On the hand, time behaviours of m=2/n=1 FBs in Rax=0.92 m are shown in Fig.2. The amplitude of magnetic fluctuations grows in the rising phase of the net plasma current and then the sawtooth oscillations characterized by the annular crash near the q=2 surface(at $\rho \sim 0.5$) are induced in the latter half of the discharge. Both of m=3/n=2 and m=2/n=1 FBs show rapid frequency sweep by about factor of two in each burst(Fig.3). This frequency sweep is not caused by the change in the plasma potential near the rational surface. Appearance of FBs is very sensitive for the net plasma current. Radial profiles of SX-fluctuations related to FBs have two peaks in the region of $\rho < 0.7$, exhibiting ballooning nature(Fig.4). The largest peak is located near the plasma axis. This seems to suggest that two rational surfaces related to FBs are produced by beam driven current with a peaked profile. If this q-profile with two rational surfaces is realized, the current driven internal kink can be destabilized preferentially near the inner rational surface, having a character of pressure driven interchange mode at the outer rational surface in the finite beta plasma[10]. If the orbits of toroidally and/or helically trapped ions are assumed to be equivalent for the banana orbit in a tokamak, the toroidal precession frequency of trapped ions may be approximated by $f_{pre} \sim (m/n)E[1-(R_t/R)^2]/(2\pi Z r_s R B_t)$, where E, R_t, r_s and Z are the injection beam energy, the tangency radius of the beam line, the size of the rational surface and the charge of injected beam, respectively. If the size of the inner rational surface is adopted, the resonance frequency nf_{pre} is estimated to be ~90 kHz for m=3/n=2 FBs (Fig.3) and ~40 kHz for m=2/n=1 FBs. These values are close to the observed frequencies at the beginning of each burst.

3. TOROIDAL ALFVEN EIGENMODES

In TAE experiments, hydrogen beam is injected into a hydrogen plasma, where the toroidal field, line averaged electron density and beam energy are scanned in the range of B_t=0.7 - 1.5 T, n_e=0.5 - 3 x $10^{19}m^{-3}$ and E=28-40 keV, respectively. In the condition, n=1 and n=2 TAEs having very narrow frequency band width(≤ 1 kHz) are observed in inward-shifted(Rax=0.92m) and outward-shifted(Rax=0.95m) plasmas[7]. Excitation of TAEs are sensitive for a small net plasma current which decreases the magnetic shear near the plasma core region. Figure 5 summarizes the observed frequencies of TAEs as a function of the calculated TAE frequency for pure hydrogen plasma $f_{TAE}(0)$, where the electron density at the plasma center is employed and q=(m+1/2)/n. As seen from Fig.5, the observed frequencies are in proportion to the TAE frequency. However, the values are by about 30% lower than the TAE frequency. In these plasmas, Zeff=2-3 and then impurity ions decrease $f_{TAE}(0)$ by about 15 %. On the other hand, since the TAE gap position is expected to be r=0.3-0.4 typically, this effect increases $f_{TAE}(0)$ by ~5%. Therefore, the observed frequencies are still by ~20% lower than $f_{TAE}(0)$. The TAE frequency and TAE gap position are approximately predicted by simple calculation of the Alfven continua in a cylindrical configuration. Figure 6(a) shows the (uncoupled) Alfven continua for n=1 and n=2 TAEs observed in CHS, where the above-mentioned impurity effect is taken into account in the calculation. This figure also shows the TAE gap structure calculated by the approximate expression for large-aspect-ratio and low beta tokamak[3]. Here, the rotational transform(1/q) is assumed to be the sum of the rotational transform due to the net plasma current and the external rotational transform in three dimensional current-free equilibrium with 0.2 % averaged total beta. Here, the current density profile is assumed to be a plausible shape of $j_\varphi = j_o(1-\rho^2)^2$. As seen from Fig.6, the observed frequency (~ 97 kHz) lies near the lower boundary of the innermost TAE gap. Internal structure of TAEs is measured by the SX array. Figure 6(b) shows the radial profiles of coherence γ between SX signal and magnetic probe signal for the observed n=1 TAEs. This figure shows that high coherence region is in the core region($\rho \leq 0.6$), where γ for noise is ~0.3. Note that high coherence observed around the plasma center is caused by the integral effect of SX emission along the line of sight. Therefore, TAEs are predicted to be localized around ρ ~ 0.2-0.6, which is also confirmed by the profile of plasma potential fluctuations measured by heavy ion beam probe[7]. This result is consistent with Fig.6(a). The core localization of TAEs seems to be similar to the core localized TAEs in a tokamak[12]. It is also required for excitation of TAEs in CHS that the ratio of the beam velocity to the central Alfven velocity V_b/V_A exceeds about 0.5. This suggests the side-band excitation of TAEs[13].

4. SUMMARY

In the CHS heliotron/torsatron, m=2/n=1 and m=3/n=2 fishbone instabilities(FBs) are observed in NBI heated plasmas where the beam driven current with a peaked profile is induced. Energetic ion loss is transiently enhanced by FBs. In each FB-burst the frequency of the magnetic fluctuations is considerably swept down. Radial profiles of the fluctuations suggest that the current driven internal kink mode might be destabilized by energetic ions, having a character of pressure driven interchange mode in the finite beta plasma. However, these FBs are easily stabilized by suppressing beam driven current. In addition, n=1 and n=2 TAEs are also identified for the first time in NBI heated plasmas. TAEs are excited only when the ratio of beam velocity to the Alfven one exceeds 0.5 and a net plasma current induced by co-NBI is in the required level depending on B_t. The observed TAEs localize near the plasma core region with fairly low magnetic shear realized by the net plasma current. TAEs in CHS do not enhance energetic ion loss, because the fluctuation level is low ($b_\theta/B_t < 10^{-5}$ at LCFS).

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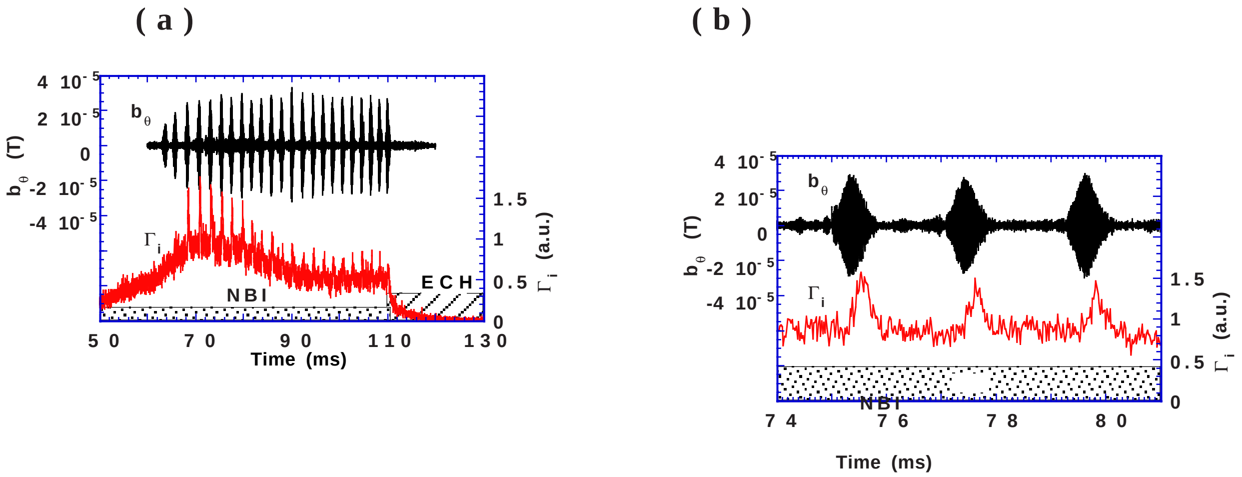

Fig.1 (a) Time evolution of magnetic fluctuations of m=3/n=2 FBs and energetic ion loss flux in the outward-shifted plasma of Rax=0.97 m, where Bt=0.9 T, line averaged electron density~0.8×10^{19} m^{-3} and peak plasma current ~ 6 kA. **(b)** expanded time trace of Fig.(a).

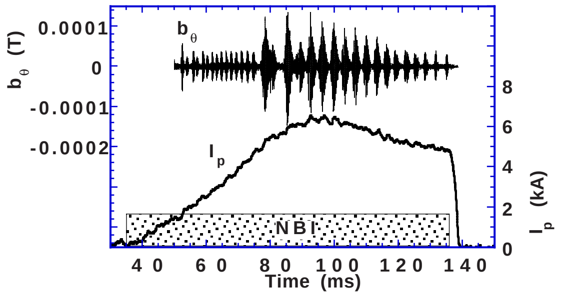

Fig.2(a)

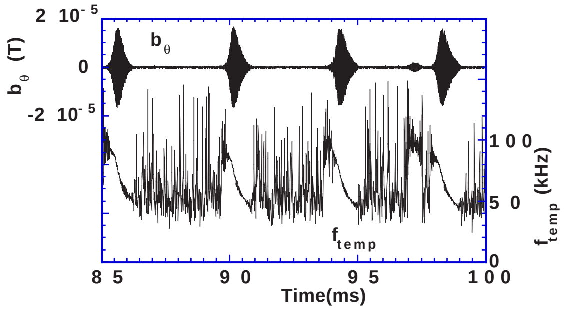

Fig.3

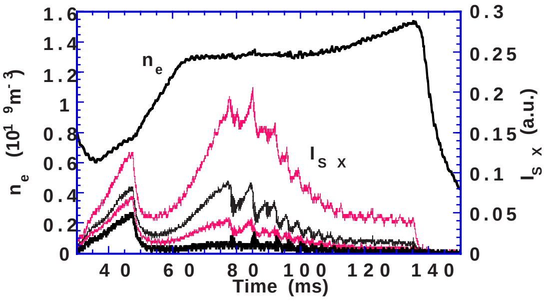

Fig.2(b)

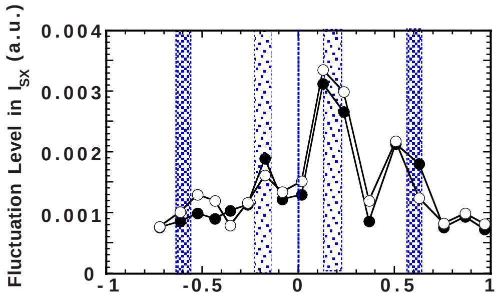

Fig.4

Fig.2 (a) Time evolution of magnetic fluctuations of m=2/n=1 FBs in the inward-shifted plasma of Rax=0.92 m at Bt=0.9 T. **(b)** sawtooth crashes induced by FBs are observed in the SX-signals.
Fig.3 Detailed behaviours of magnetic fluctuations of m=3/n=2 FBs and temporal frequency .
Fig.4 Radial profiles of soft X-ray fluctuations during two bursts of m=2/n=1 FBs. Shaded zones indicate the predicted rational surfaces of q=2.

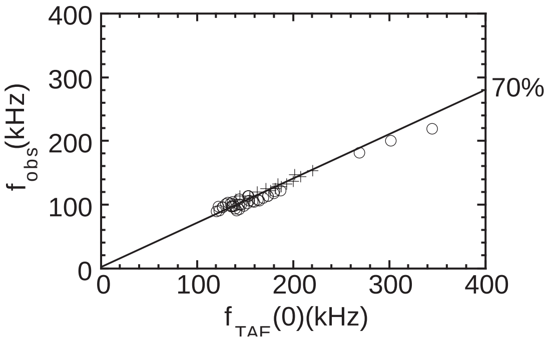

Fig.5

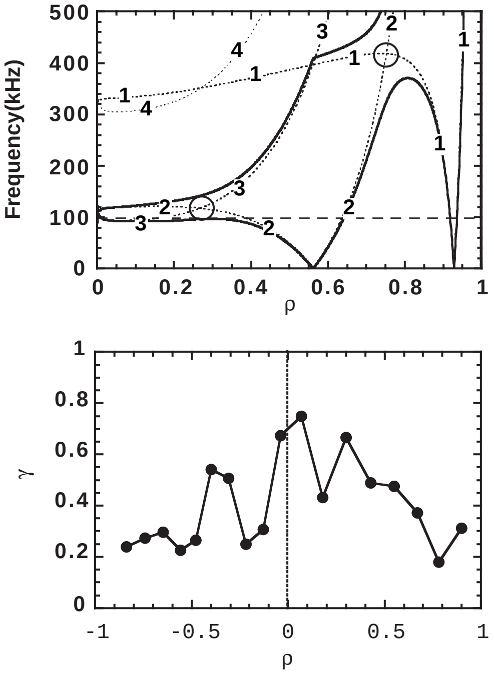

Fig.6(a) and (b)

Fig.5 Comparison of observed frequencies of TAEs with the calculated TAE frequencies.
Fig.6 (a) Alfven continua calculated in the cylindrical configuration for n=1TAE observed in CHS, and TAE gap structure calculated from the approximate expression in large-aspect-ratio and low beta tokamak. The horizontal line indicates the observed frequency, **(b)** Radial variation of coherence between SX signals and magnetic fluctuations of n=1TAE, where the high coherence region around the center is due to the pass-integral effect in SX-signals.