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Impact of Energetic Ion Driven Global Modes on Toroidal Plasma Confinements

TOI Kazuo, YAMAMOTO Satoshi[1], TAKECHI Manabu[2], NAKAJIMA Noriyoshi,
ISOBE Mitsutaka, TAKAGI Shoji[1], MATSUNAGA Go[1], OHDACHI Satoshi,
SAKAKIBARA Satoru, OSAKABE Masaki, SASAO Mamiko, KOTANI Jyunichi[1],
CHS and LHD Experimental Groups

National Institute for Fusion Science, Toki 509-5292, Japan
[1]Dep. Energy Eng. and Science, Nagoya Univ. Nagoya, Japan
[2]Japan Atomic Energy Research Institute, Ibaraki, Japan

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Abstract

Excitation of energetic-ion-driven Alfvén eigenmodes (AEs) and their impact on energetic ion confinement are widely and intensively studied in helical devices such as CHS and LHD as well as major tokamaks. The excitation of AEs sensitively depends on the parameter space defined by the averaged beam beta $<\beta_{b\|}>$ and the velocity ratio $V_{b\|}/V_A$ ($V_{b\|}$: injected beam ion velocity, V_A: Alfvén velocity). In LHD, these two relevant parameters are widely scanned without suffering from current disruptions. So far, toroidicity induced AE (TAE), global AE (GAE) and energetic particle mode (EPM) or resonant TAE (R-TAE) were identified during tangential neutral beam injection (NBI) in CHS and LHD. Moreover, a new coherent mode with the frequency by about 8 times higher than the TAE frequency was observed in NBI heated plasmas of LHD at low magnetic field (≤0.6T). This mode may be induced by helical field components of the confinement field. Nonlinear phenomena of bursting amplitude modulation and fast frequency chirping are clearly seen for TAEs and EPMs in CHS and LHD. EPMs in CHS and bursting TAEs in LHD enhance radial transport of energetic ions in certain plasma conditions.

Keywords:

Alfvén eigenmode, TAE, HAE, EPM, energetic ion, toroidal plasma, heliotron/torsatron, alpha particle

1. Introduction

In a D-T burning plasma, alpha particles generated by fusion reactions would excite Alfvén eigenmodes (AEs) and other energetic-ion-driven global modes, and then might be expelled outside the plasma confinement region by these global modes. The alpha-particle-driven modes and their effects on alpha particle confinement attract much attention from a point of view of a D-T burning plasma in ITER [1]. It is particularly important to accurately predict the linear growth and damping rates of AEs and establish the stabilization methods. For this reason, the interaction between energetic ions and Alfvén waves are intensively being studied by using NBI, ICRF heating and alpha particles in not only major tokamaks but also helical devices. Toroidicity induced Alfvén eigenmodes (TAEs), global AEs (GAEs) and energetic particle modes (EPMs) or resonant TAEs (R-TAEs) are commonly observed in these experiments in tokamaks and helical devices.

The energetic ion drive of TAE or the linear growth rate (γ) is approximately expressed as [2]:

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

$$\gamma/\omega_o = \frac{9}{4} <\beta_{b\parallel}> [\omega^*_{b\parallel}/\omega_o - 0.5] F\,(V_A / V_{b\parallel})$$

where $\omega^*_{b\parallel}$ and ω_o are respectively the energetic ion diamagnetic drift angular frequency and mode angular frequency, and F is related to the fraction of ions that resonate with the Alfvén wave. The velocities V_A and $V_{b\parallel}$ are the Alfvén velocity and energetic ion velocity, respectively. Parameter space typically scanned for AE-studies in various toroidal devices is schematically shown in Fig. 1. The parameter space in large tokamaks covers the region predicted in ITER [1]. It should be noted that very wide range of these parameters is scanned in LHD plasmas because they do not suffer from any current disruptions. These parameters are further widely scanned in a spherical tokamak NSTX because of very low toroidal field [3].

In this paper, we summarize experimental results on energetic-ion-driven AEs obtained in CHS and LHD, comparing with those from several major tokamaks and W7-AS shearless stellarator.

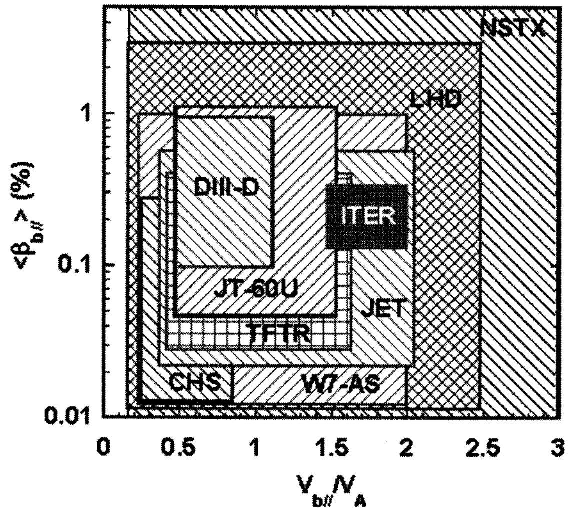

Fig. 1 Parameter space scanned for Alfvén eigenmode studies in various toroidal devices.

2. Alfvén eigenmodes in a toroidal plasma

We now summarize Alfvén eigenmodes in a toroidal plasma which has the following magnetic field expressed by the Boozer coordinate (ψ, θ, ϕ).:

$$B/B_o = 1 + \sum_{\mu,\nu} \varepsilon_B^{\mu,\nu}(\psi)\cos(\mu\theta - \nu N\phi)$$

where B_o is the averaged field strength, $\varepsilon_B^{\mu,\nu}$ is the amplitude of each Fourier component and N is the field period (N=8 for CHS and N=10 for LHD). When two following cylindrical Alfvén branches intersect with each other, various spectral gaps are produced, that is,

$$\omega = k_{\parallel m,n} V_A = - k_{\parallel m+\mu, n+\nu N} V_A \,.$$

The numbers m and n are the poloidal and toroidal mode numbers, respectively. From this equation, a general expression of the gap frequency is derived as follows:

$$f^{\mu,\nu} = \left| N\nu q^* - \mu \right| \frac{V_A}{4\pi R q^*}\,,$$

where q^* and R are the safety factor at the gap position and the major radius, respectively. The quantity $V_A/(4pRq^*)$ corresponds to the TAE gap frequency. The gap location is determined by the radial position of q=q^*, where

$$q^* = \frac{2m+\mu}{2n+\nu N}\,.$$

The TAE corresponds to the case of μ=1, ν=0, and EAE to μ=2, ν=0. The Alfvén eigenmode induced by helical component $\cos(2\theta - N\phi)$ corresponds to the case of μ=2, ν=1 which is termed as HAE [4,5]. It should be noted that the gap width is approximately proportional to the amplitude of the relevant Fourier component $\varepsilon_B^{\mu,\nu}$ and the mode frequency. Therefore, the width of HAE can usually be much wider than TAE gap for helical devices with large N such as LHD (N=10). Moreover, the resonance condition between energetic ions and AEs is expressed as,

$$V_{b\parallel}/V_A = \frac{1}{1 \pm 2/(\nu N q^* - \mu)}$$

Accordingly, the resonance condition for HAE in LHD is similar to that for TAE.

3. Excitation of Alfvén Eigenmodes by energetic ions

Various aspects related to AE- excitation are being investigated in major tokamaks. Here, we only point out two interesting observations: "core localized TAE" and "Alfvén cascade" that are closely related to AEs in CHS and LHD. As mentioned in Section 2, characteristics of AEs sensitively depend on the rotational transform (1/q-) profile. As seen in Fig. 2, a heliotron/torsatron type device such as CHS and LHD has a reversed shear configuration (dq/dr<0) over the whole minor radius in the low plasma beta. In CHS or LHD, the TAE gap frquency tends to increase toward the plasma edge due to a character of the increasing function of the rotational transform for the minor radius. Because of this situation, core localized type of TAE may be more likely in CHS or LHD because it would not be suppressed by strong continuum damping near the edge.

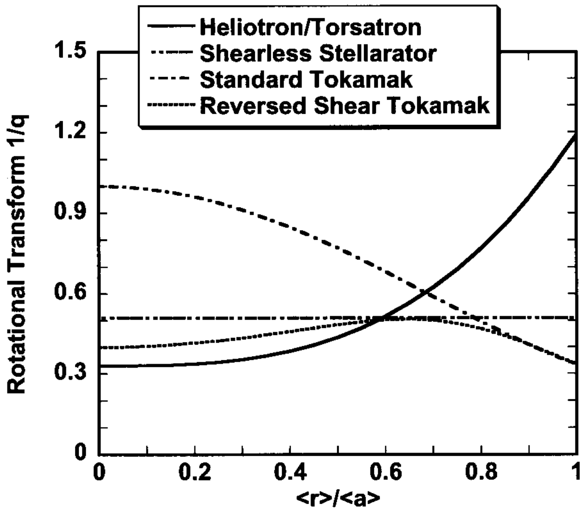

Fig. 2 Radial profiles of the rotational transform schematically drawn for tokamaks and helical devices.

The core localized TAE in a tokamak plasma was for the first time identified in TFTR by measuring the internal structure with refrectometer [6]. In a helical plasma, the presence of core localized type TAEs was first revealed in CHS by the direct measurement of the internal structure with a soft X-ray (SX-) detector array and heavy ion beam probe [7-9]. An example of LHD shown in Fig. 3 also suggests a core localized type TAE. In CHS, both TAE and EPM with m~2/n=1 are often observed in the inward-shifted plasmas, together with low frequency (LF) mode (<5kHz). In the plasma, the radial profiles of SX-fluctuations and their phase for n=1 TAE, m~2/n=1 EPM and m~2/n=1 low frequency (LF) mode are measured by the SX array, as shown in Fig. 4. The n=1 TAE is localized near the plasma center and m~2/n=1 EPM is well inside the q=2 rational surface, while m~2/n=1 LF mode has a peak near the q=2 surface exhibiting the character of interchange mode.

Recent new observation of AEs in reversed shear plasmas of JET is so called Alfvén cascade that mainly upward frequency sweep takes place and the time evolution of the frequency clearly reflects that of the minimum q value, $q_{\min}$ [10]. This phenomenon may be employed as a diagnostic tool for measurement of $q_{\min}$ in a reversed shear plasma. Note that TAE exhibiting relatively slow frequency chirp-up and down similar to Alfvén cascade in JET was also observed in LHD, although the underlying physics is not yet clarified [11].

TAEs in LHD are excited in the condition of $\langle\beta_{b\|}\rangle$=0.01–3% and $V_{b\|}/V_A$=0.3–2.2, and for EPMs $\langle\beta_{b\|}\rangle$=0.08–3% and $V_{b\|}/V_A$=0.1–1.5, respectively [12]. Nonlinear phenomena of bursting amplitude modulation and fast frequency chirping are typically seen in TAEs and EPMs observed in CHS and LHD [8]. These nonlinear phenomena seem to closely link to enhanced transport of energetic ions. This will be discussed in the following Section 4.

It should be noted that a new coherent mode with the frequency by about 8 times higher than TAE gap frequency was observed in NBI heated LHD plasmas at low magnetic field (≤0.6T). A typical example of the mode is shown in Fig. 5. This mode may be induced by helical field components of the confinement field. So far, the high frequency mode is detected in the parameter region of $\langle\beta_{b\|}\rangle$~0.8–2% and $V_{b\|}/V_A$~1.6–2.2.

In shearless stellarator W7-AS, low n global Alfvén eigenmodes GAEs are most likely and dangerous modes because the magnetic shear is almost vanishing and then the frequency is much lower than that of TAE [13]. In CHS and LHD, n=0 GAE was sometimes excited, but n=1 GAE was rarely observed in CHS[14].

4. Effects of energetic ion driven Alfvén eigenmodes on energetic ion transport

TAEs and EPMs sometimes enhance radial transport of energetic ions in tokamak plasmas. The loss sensitively depends on the amplitude of radial magnetic fluctuations. The clear correlation was observed in DIII-D [15]. The loss in JT-60U is mostly enhanced when AEs have a character of bursting amplitude modulation and fast frequency chirping [16].

Particle orbit trajectory in CHS or LHD is very different from that in a tokamak plasma where has only two kinds of particle orbit: passing and trapped (banana) orbits. That is, four classes of particle orbit are present because of helical ripple as well as toroidicity. To avoid trapped ion loss, neutral beams are injected almost tangentially in CHS and LHD. Slowing down process is dominant in CHS and LHD because the beam energy is much higher than the electron temperature.

In CHS, energetic ion loss flux and the pitch angle was measured by using a scintillator-based lost-ion probe [17]. According to orbit calculation of energetic ions, these ions are lost in poloidally and toroidally localized zone on the vacuum vessel wall. Therefore, the lost ion probe was placed near such narrow zone inside the vacuum vessel. Figure 6 shows time evolution of lost ion flux and m~3/n=2 EPM observed in the so-called outward-shifted configuration of CHS. The

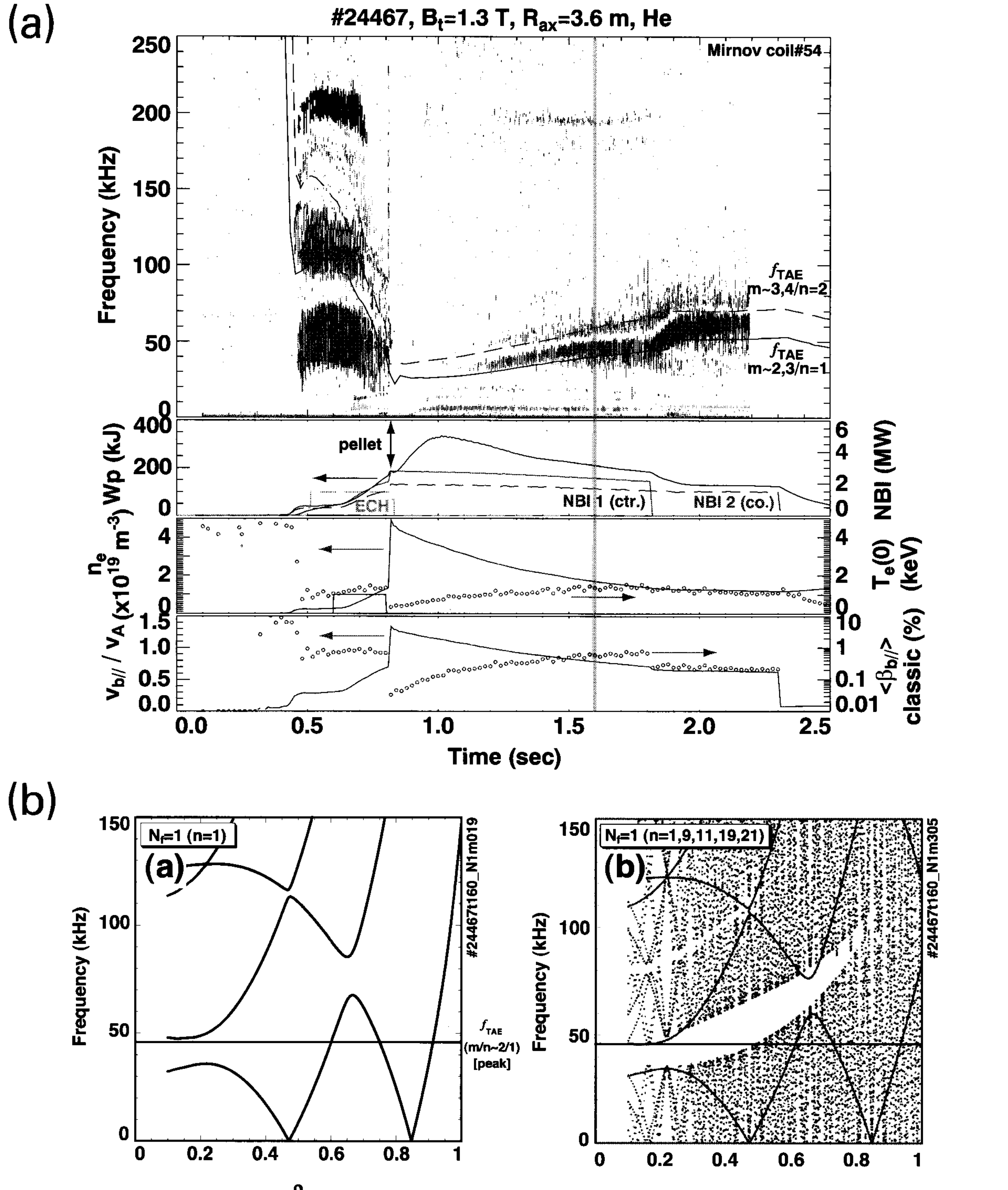

Fig. 3 (a) Time evolution of the frequency of magnetic fluctuations and plasma parameters (W_p: stored energy, NBI: NBI power, n_e: line averaged density, $T_e(0)$: electron temperature at the plasma center, $V_{b\parallel}/V_A$: ratio of injected beam velocity to the Alfvén velocity, $<\beta_{b\parallel}>_{classic}$: beam beta value based on classical slowing down) in the LHD inward-shifted configuration of R_{ax}=3.6 m at the toroidal field B_t=1.3 T. The solid and broken curves in the top frame indicate the calculated frequencies for m=2+3/n=1 TAE gap and m=3+4/n=2 one, respectively. (b) The shear Alfvén spectra for n=1 mode in two dimensional and three dimensional cases. In the latter case, the toroidal mode coupling among N_f=1 mode family is taken into account. The horizontal line indicates the observed frequency.

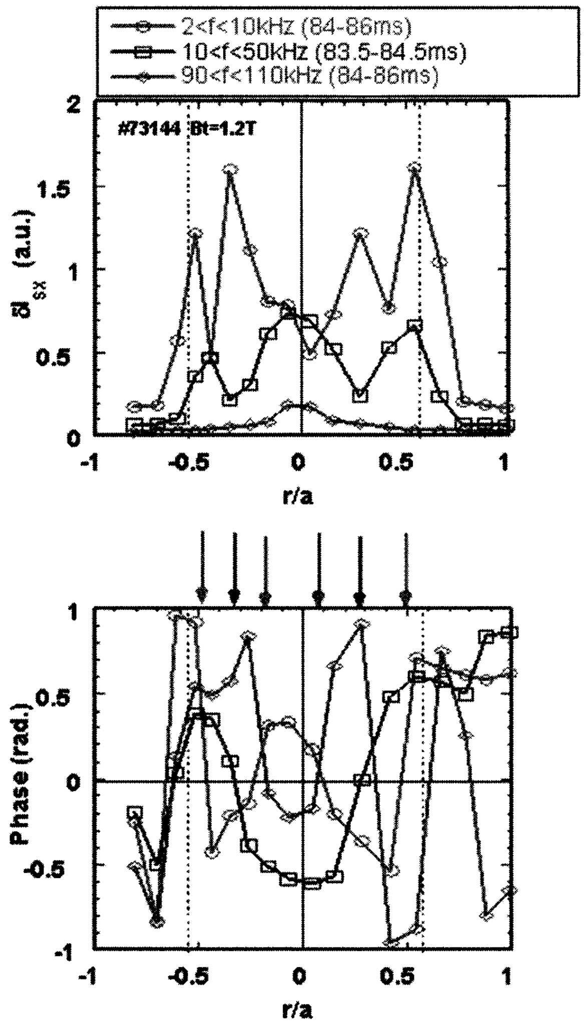

Fig. 4 Radial profiles of SX-fluctuation amplitude and phase for TAE, EPM and LF mode with m~2/n=1 in CHS. The locations of the phase jump for respective modes are respectively near the plasma center for TAE, slightly outside but inside the q=2 surface for EPM, and close to q=2 surface.

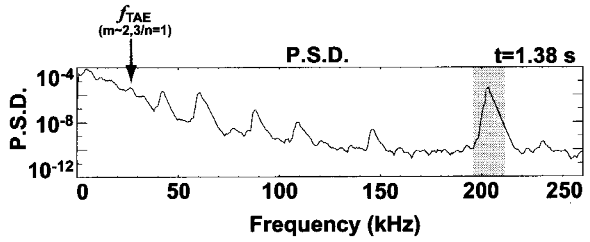

Fig. 5 Power spectrum of magnetic probe signal obtained in LHD. The peak around f~200 kHz corresponds to the high frequency mode. The frequency related to m~2+3/n=1 TAE gap is about 25 kHz.

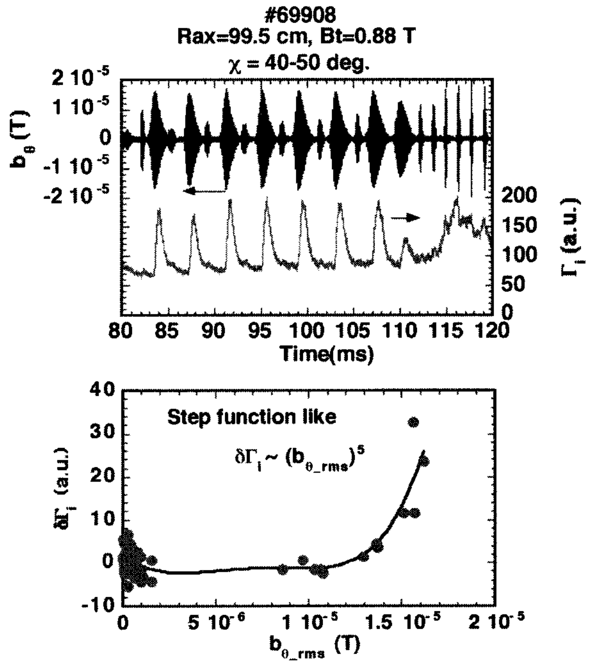

Fig. 6 Time evolution of magnetic fluctuations of m~3/n=2 EPM and energetic ion loss flux measured with a scintillator probe. The lower figure shows the transient increment of the energetic ion loss flux as a function of the EMP amplitude.

increment of loss flux $\delta\Gamma_i$ due to EPM magnetic fluctuations $b_{\theta rms}$ is also shown as a function of the magnetic fluctuation amplitude. The functional relation is expressed as

$$\delta\Gamma_i \propto (b_{\theta rms})^s,$$

where s=5. When s=1 and s=2 respectively correspond to resonant convection loss and diffusive transport of energetic ions [18]. The case of s>2 means the case of the destruction of magnetic surface. In CHS, this large value of s may link to the presence of loss cone.

Rapid growth of m~2/n=1 EPM in inward-shifted plasmas of CHS interrupts the TAE activity, of which phenomenon can be interpreted by the reduction of the beam pressure and its radial gradient caused by enhanced transport of beam ions around the peak position of TAE. The decrease in the energetic ion pressure due to m~2/n=1 EPM is also inferred from the transient decrease of the Shafranov shift correlated with each EMP burst, of which Shafranov shift was derived from the peak position of soft X-ray emission [19]. In LHD, bursting TAE transiently depresses the bulk stored

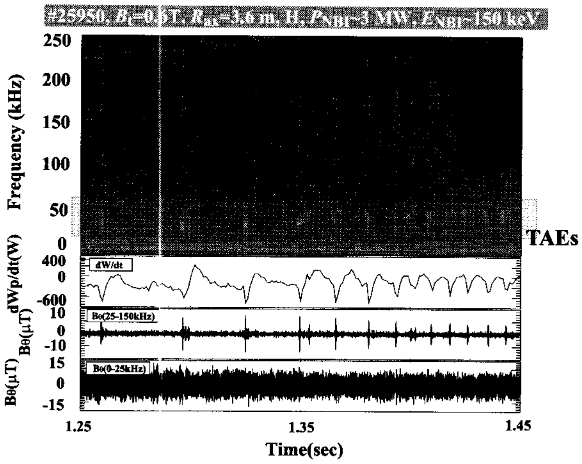

Fig. 7 Time evolution of the frequency of magnetic fluctuations, time derivative of the stored energy and filtered magnetic fluctuation amplitudes. The fluctuations in the range of 25 kHz to 150 kHz correspond to the bursting TAE.

energy Wp (Fig. 7). The reduction rate ($-dW_p/dt$) corresponds to about 15% of NBI power input. This suggests at least ~15% loss of energetic ion pressure [12]. Moreover, we show a clear example of CHS in Fig. 8 where m~$2/n$=1 EPM having the amplitude of ~1–2 G at the magnetic probe position degrades the bulk confinement considerably (~10–20% reduction in Wp). In this particular shot, the stored energy and electron density recover by about 20% when m~$2/n$=1 EPM is occasionally stabilized. Note that this stabilization of EPM is not caused by the elimination of q=2 surface because LF interchange mode is again destabilized at higher plasma current ~15 ms before the turn- off of NBI. Moreover, weak TAEs are excited by energetic ions in this EPM suppression phase. The cause of the suppression of EPM is not yet clarified.

In W7-AS [20], GAEs and bursting AEs sometimes enhance energetic ion loss as similar to the loss due to TAEs in tokamaks and LHD.

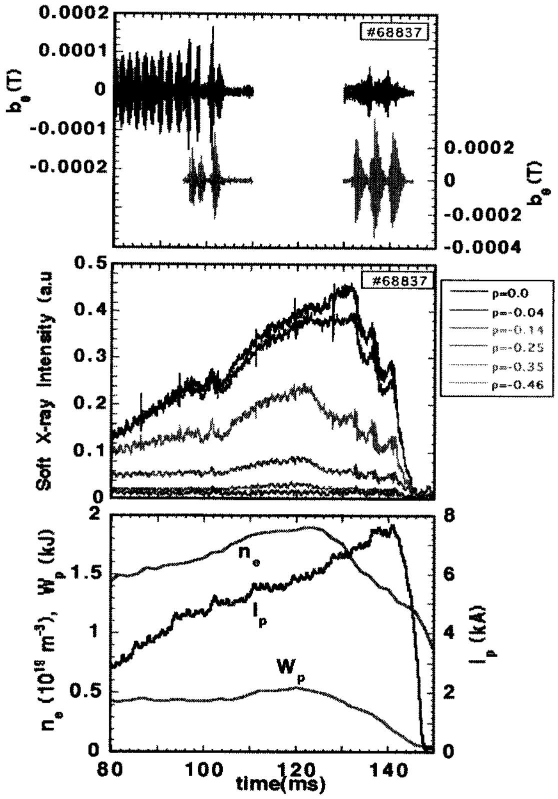

Fig. 8 Time evolution of magnetic fluctuations of m~$2/n$=1 EPM, soft X-ray emissions, and line averaged electron density, the stored plasma energy and plasma net current. The quiescent phase is in the time window from 104 ms to 132 ms. The upper trace in the top frame shows magnetic fluctuations of m~$2/n$=1 EPM, and the lower one to low frequency m=$2/n$=1 interchange modes. Note that both fluctuation amplitudes stay the lowest level from 110 ms to 130 ms, but are not shown in this figure.

5. Summary

Energetic ion driven Alfvén eigenmodes are intensively being studied in three helical devices LHD, CHS and W7-AS as well as in major tokamaks. A lot of more general information about Alfvén eigenmodes excited by energetic ions was obtained, that is, TAEs, EAEs, EPMs and GAE were identified as are predicted by MHD theories including energetic ions. However, quantitative comparison between experiments and theories is still preliminary. In helical devices such as LHD, very wide parameter range is being explored without suffering from current disruptions. These researches contribute to improved understanding of Alfvén eigenmode in toroidal plasmas, as well as the physics design of a fusion reactor based on helical configurations.

Future studies of AEs in CHS and LHD are aiming at experimentally obtaining complete sets of shear Alfvén spectra through Alfvén spectroscopy, and clarifying physics related to interaction between Alfvén waves and energetic ions.

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