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Energetic ion driven MHD instabilities in high β LHD plasmas

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Introduction

MHD instabilities destabilized by the energetic ions are being studied in many magnetic confinement devices because there are two important and of interest issues for plasma confinement. One is to clarify the characteristics of these energetic ion driven MHD modes. The other is to clarify the effects of the MHD instabilities on energetic ion transport and bulk plasma confinement. In particular, these researches are extensively being studied in many tokamaks with regard to alpha particle physics on ITER.

These MHD instabilities are also being studied in helical systems, which are thought to be promising alternative concepts for the tokamaks. Toroidicity induced Alfvén eigenmodes (TAEs) and energetic particle modes (EPMs), which are destabilized by the energetic ions, were observed in the Compact Helical System (CHS)[1,2], Wendelstein-7AS (W-7AS) [3] and the Large Helical Device (LHD) [2,4]. However, knowledge about these modes in helical systems is still unclear due to a complex magnetic configuration. Alfvén eigenmodes (AEs) are predicted to be more unstable in a high beta plasma of LHD from the previous studies. In this paper, we report two topics about energetic ion driven MHD instabilities in high beta LHD plasmas.

TAEs in high beta LHD plasmas and loss of energetic ion caused by TAEs

In NBI heated LHD plasmas at low magnetic field (B_t < 1 T), the bursting TAEs are often observed, of which amplitude is one order of magnitude larger than non-bursting ones. A typical high beta discharge that TAEs are observed is shown in Fig.1, where the absorbed NBI power is 2.7 MW and hydrogen beams with E_{NBI} = 150 keV are tangentially injected into a hydrogen plasma in the inward-shifted configuration at the magnetic field B_t = 0.5 T. In this high beta LHD plasma, m~2-3 / n=2 TAE is observed, of which gap is formed by the poloidal mode coupling of m=2 and 3 modes, and m~2-3 / n=1 TAE is also observed. The TAE with m~2-3 / n=1 disappears at t = 0.8 sec because the TAE gap is disappeared due to considerably modification of the rotational transform profile caused by the finite beta effect and the net plasma current.

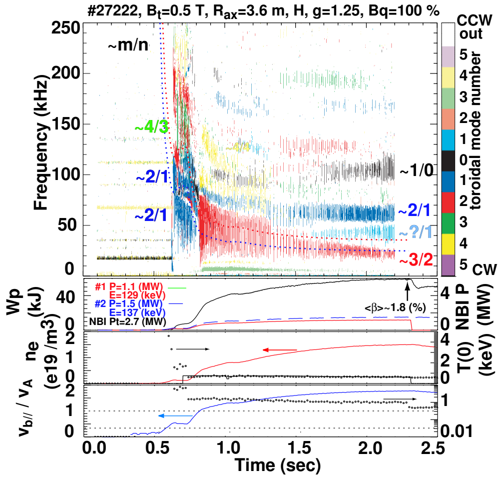

Fig.1, Time evolution of magnetic fluctuations in a high beta NBI-heated LHD plasma. The bursting TAEs are

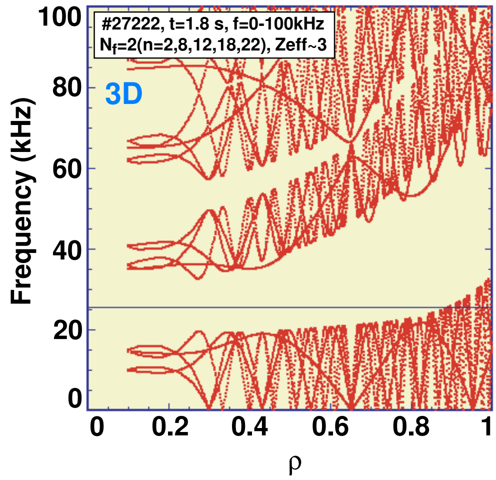

Fig.2, The shear Alfvén spectra with N_f = 2 at t = 1.8 s of the plasma shown in Fig. 1. The spectra are calculated for the 3D magnetic configuration.

We compare the observed frequencies at t = 1.8 s is the plasma shown in Fig. 1 with the shear Alfvén spectrum that is calculated for 3D magnetic configuration. Here the toroidal mode coupling is taken into account. A heliotron configuration has a 3D magnetic configuration having the toroidal field period number N_p. A family of modes with toroidal mode number n' satisfying the relation $n'+n$ or $n'-n = kN_p$ (k = ….-2,-1,0,1,2….) can couple with the mode having the toroidal mode number n [5]. In LHD case, the N_f = 2 mode is composed by Fourier modes with n' = …-12, -8, -2, 2, 8, 12, ...etc. The toroidal mode coupling among n = 2,8,12,18,22 and 28 Fourier modes is taken into account for the calculation of the spectrum shown in Fig. 2. The gap structures are produced through poloidal mode coupling for all Fourier modes with different toroidal mode number in the same mode family. This leads to the formation of the envelope of all these TAE gaps. Good alignment of the TAE gap from the plasma core towards the edge can be realized by the large Shafranov shift and the decrease of the magnetic shear in such high beta case. The good alignment of the gap structure and high bema beta $<\beta_{b//}>$ are thought to be responsible for the excitation of TAE with large amplitude.

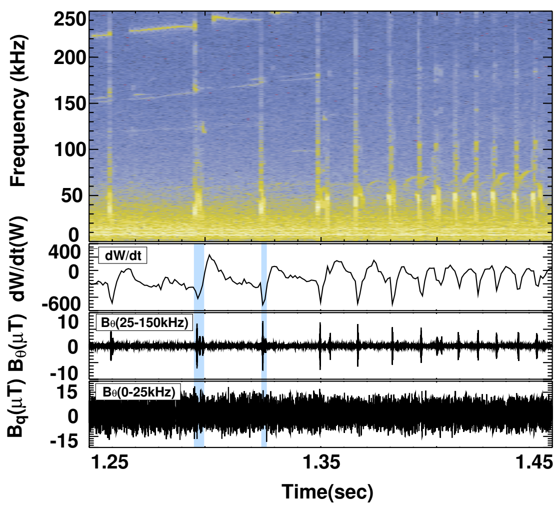

Fig. 3, Time evolution of magnetic fluctuations and time derivative of the stored plasma energy dW/dt.

The TAEs appreciably affect the energetic ion transport and/or bulk plasma confinement because some plasma parameters are simultaneously modulated with bursting TAEs, as shown in Fig. 3. The transient decrease in the stored energy ($dW/dt<0$) is explained by the transient loss of energetic ions in the course of the slowing down. The transient decrease in W corresponds to about 15% loss of the absorbed beam power by each burst. The loss rate of absorbed beam power is increased with the increase in fluctuation amplitude of TAEs. In the highest beta plasma, where $<\beta_{bulk}>$ ~ 2.5 % at low magnetic fields (B_t < 0.7 T), TAEs aren't observed because the resonance condition might not be satisfied.

The observation of helicity induced Alfvén eigenmodes (HAEs)

The MHD instabilities, of which frequency is eight times higher than that of TAE gap, are newly observed in NBI heated plasmas of LHD at the low magnetic fields (B_t < 0.7 T). The typical discharge where these modes were observed is shown in Fig. 4, where hydrogen beams are injected into H plasma in the configuration of R_{ax} = 3.6 m at B_t = 0.5 T. The coherent modes in the range of 180 ~ 220 kHz are observed after t = 1 s. The magnetic fluctuation amplitude reaches $b_\theta/B_t \sim 10^{-6}$ at the probe position. The observed modes are identified to be n = 2 and propagate in the diamagnetic drift direction of energetic ion. These modes are thought to be Alfvén eigenmode (AE), because the frequencies of these modes are scaled 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 helicity induced AEs (HAEs) [5,6] can be excited. The frequencies of these modes are by 40 % lower than the predicted HAE gap frequency. However, the full width of the HAE gap is considerably wide (~200 kHz in this case). The observed modes are thought to be related to the HAEs.

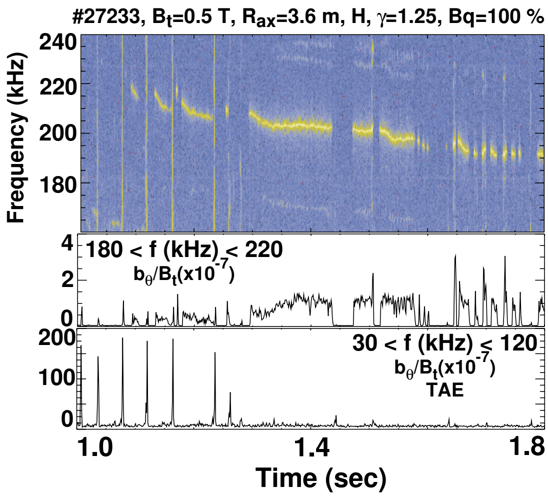

Fig. 4, The high frequency modes with n = 2 are observed in a NBI-heated plasma.

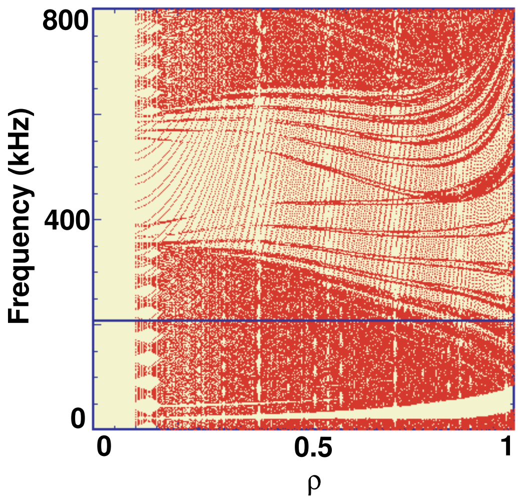

Fig.5, The shear Alfvén spectra with N_f = 2 at t = 1.4 s of the plasma shown in Fig. 4. The HAE gap is generated around f~400 kHz by the toroidal mode coupling.

We compare these observed frequencies at t = 0.8 s of the plasma shown in Fig. 4 with the shear Alfvén spectrum for N_f = 2(Fig.5.), where the toroidal mode coupling among n = 2, 8, 12, …48, 52, (including 13 kinds of n and 919 modes), is taken into account. 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 new continua inside HAE gap might be produced by the absence of helical symmetry of helical field components [7]. 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. 5 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 strongly suffered from continua damping but mode are excited. The profile of energetic ion pressure is predicted to be flat because the larmor radius of passing energetic ion reaches up to 10 % of plasma radius. Therefore, the gradient of energetic ion pressure 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 HAEs are observed for the first time in helical systems.

Summary

We investigated energetic ion driven MHD instabilities in NBI heated high beta LHD plasmas. The m~2-3/n=2 bursting TAEs with large amplitude are observed and appreciably affect the energetic ion transport. About 15% of the absorbed beam power is lost by each burst. The high frequency MHD instabilities are newly observed in NBI heated plasmas of LHD. As a result of a comparison with the shear Alfvén spectrum that in full 3 dimensional magnetic configurations, the frequency of observed modes lies in the HAE gap near the plasma edge. The observed modes are thought to be HAEs.

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