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MHD Instabilities Destabilized by Energetic Ions on Large Helical Device

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Abstract

In the Large Helical Device (LHD), two types of coherent magnetic uctuations driven by energetic ions are observed in neutral beam heated plasmas at low toroidal magnetic field ($B_t \simeq 1.5$ T). One is a toroidicity induced Alfvén eigenmode (TAE) with the toroidal mode number $n = 1$ and $n = 2$, and the other a shbone-like burst mode with $m = 2/n = 1$ (m: poloidal mode number).

Keywords:

energetic ion, TAEs, burst mode, MHD instabilities, Large Helical Device

1. Introduction

To clarify excitation and damping mechanisms of MHD instabilities which would be destabilized by alpha particles is one of the most important issues for steady state burning physics of a toroidal plasma. It is predicted that energetic alpha particles can resonate with MHD fluctuations and drive them unstable. This kind of wave-particle interactions can induce direct alpha particle loss from the plasma before the thermalization so that the fusion burn would not be sustained. These ejected energetic alpha particles might also lead to significant damage of the first wall in a fusion device. Energetic ions produced by NBI and/or ICRF also would excite these MHD instabilities, as well as alpha particles. Energeticion-driven MHD instabilities such as Alfvén eigenmodes (AEs) and fishbone instabilities are intensively studied in NBI and/or ICRF heated plasmas in many toka-maks [1,2].

Energetic-ion-driven MHD instabilities has been stud-ied also in helical devices, CHS heliotron/torsatron [3,4] and W7-AS shearless stellarator [5]. In this paper, these experimental researches on the energeticion-driven MHD instabilities are extended to high temperature plasmas in a large sized helical device LHD where a reactor relevant plasma will be confined. This paper is organized as follows. In section 2, experimental condition and diagnostics are briefly described. In section 3, the toroidicity induced Alfvén eigenmodes (TAEs) observed in NBI heated plasmas at $R_{ax} = 3.75$ m and 3.6 m are presented, where R_{ax} is the magnetic axis position of the vaxuum fields. Fishbone-like burst modes are given in Sec. 4. In Sec. 5, conclusion of this study is described.

2. Experimental Set-Up

In LHD, energetic-ion-driven-MHD instabilities are studiedin relatively low density hydrogen or helium plasmas ($\leq 2 \times 10^{19}$ m^{-3}) heated by tangential neutral beam injection (NBI). The toroidal magnetic field is

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varied from $B_t \simeq 2.9$ T to 0.75 T. The magnetic axis position of the vacuum field is adjusted to be $R_{ax} = 3.75$ m or 3.6 m. Magnetic fluctuations caused by these MHD instabilities are detected with two magnetic probes placed in two different toroidal locations by 108° away, and a set of 8 magnetic probes arranged inside the vacuum vessel along a helical coil of LHD. The toroidal mode number n is determined by the former probes. The poloidal mode number m is determined by the latter set of probes. These probes with about 2mcoaxial cable have high frequency response up to about 1 MHz and these data are acquired in 500 kHz/s sample rate. When the fluctuation amplitude is transiently changed like a burst, the propagetion direction can successfully be determined, even by two probes arranged in the toroidal direction.

3. Toroidicity Induced Alfvén Eigen-modes

In NBI heated plasmas at $R_{ax} = 3.75$ mcoherent magnetic fluctuations are observed, as shown in Fig. 1. The hydrogen plasma was heated by balanced neutral beam injection of total absorption power ~ 3.4 MWand hydrogen beam energy 130 keV, where the averaged bulk plasma beta and fast ion beta reaches 0.6% and 0.4% at $t = 0.5$ s, respectively. The coherent magnetic fluctuations in the range of 100 kHz to 200 kHz are suddenly excited in very low density phase just after NBI is switched on. After $t = 0.45$ s, magnetic fluctuations of which frequency is scaled with the dependence of $1/\sqrt{\bar{n}_e}$ are excited. In this phase, the parallel beam velocity v_b exceeds one third of the Alfvén velocity v_A, where $v_A = B_t/\sqrt{\mu_0 \rho_i}$ and ρ_i is plasma mass density estimeted by line averaged density. The toroidal mode numbers of magnetic fluctuations with thus decreas-ing frequency are identified to be $n = 1$ and $n = 2$, as shown in Fig. 1. The observed frequencies of $n=$ 1and $n = 2$ modes agree well with the TAE frequencies f_{TAE} related to respective spectrum gaps, where $f_{TAE} = v_A/4\pi qR$ and q is the safety factor at the gap. The poloidal mode numbers cannot be estimated, because the data of magnetic probes arranged hellically were not available for this shot. Considering possible poloidal mode coupling for the lowest frequency fluctuation, we assume $q = 2.5$ with $n = 1$ mode. For the other higher frequency fluctuation, $q = 1.5$ for $n =$ 1mode and $q = 1.25$ for $n = 2$ mode are assumed, respectively. These calculated TAE gap frequencies agree well with experimentaly observed ones as shown in Fig. 1. They are thought to be TAEs.

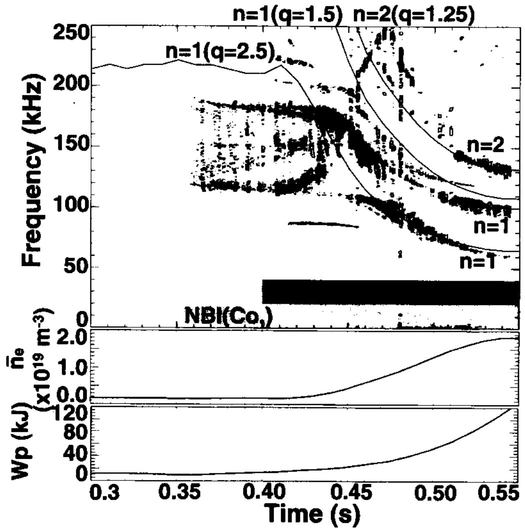

Fig. 1 Time evolution of magnetic fluctuation intensity, line averaged electron density and the stored plasma energy measered by a diamagnetic loop in NBI heated plasma at $R_{ax} = 3.75$ m and $B_t = 1.52$ T. The total NBI absorbed power reaches up to ~ 3.4 MW.

In Fig. 2, we compare the observed frequencies with the shear Alfvén gap structure which is calculated using a simplified shear Alfvén dispersion for a large aspect ratio and low beta tokamak [6]. Calculation of the TAE gap structure in the 3-dimentional configuration of LHD is required, but it is fairly complicated. In heliotron/torsatron configuration such as CHS and LHD, TAEs are not affected by the 3D configuration effect [4]. Therefore, the gap structure shown in Fig. 2 are useful to predict the possible frequency range of TAEs and the radial extent. The horizontal broken lines in Fig. 2 show the measured TAE frequencie. The $n = 1$ ($f \sim 60$ kHz) lowest frequency mode lies near the bound of the innermost gap generated by $m = 2$ and $m = 3$ poloidal mode coupling. On the other hand, two modes with $n =$ 1 ($f \sim 100$ kHz) and $n = 2$ ($f \sim 120$ kHz) lie the upper bound of the respective gaps. These three TAEs are predicted to be extented radially, because they would not suffer from strong continum damping, as seen from Fig. 2. This character is different from that of the core-localized type TAEs observed in CHS. The amplitude of these TAEs reaches to ~ 10^{-6} T at the location of the magnetic probe.

A new type $n = 1$ TAEs of which frequency is rapidly chirped upward and downward is observed in NBI heated hydrogen plasma in the further inward shifted plasma ($R_{ax} = 3.6$ m), at low toroidal field $B_t =$

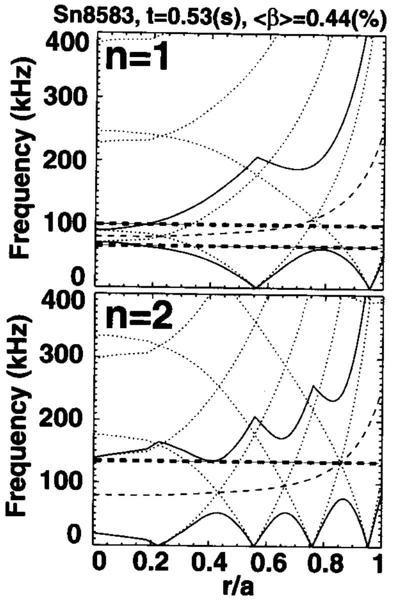

Fig. 2 (a): Shear Alfvén spectra in the cylindrical geometry (dotted curve) for $n = 1$ mode at $t = 0.53$ s of the discharge shown in Fig. 1. TAE gap structure calculated by simplified tokamak approximation is expressed by solid curves. The horizontal broken lines show the observed TAE frequencies. (b): Shear alfvén spectra for the $n = 2$ mode.

1.5 T, where line averaged electron density $\bar{n}_e \sim 1.8 \times 10^{19}$ m^{-3} and the central electron temperature $T_e(0) \sim 1.2$ keV. The time evolution of the frequency spectrum and amplitude of the "chirping" TAEs is shown in Fig. 3. The amplitude exhibits moderate amplitude modulation and reaches to $\sim 1 \times 10^{-6}$ T at the location of the magnetic probe as seen from Fig. 3. The shear Alfvén spectra are shown in Fig. 4 for the shot shown in Fig. 3. The frequency of the TAEs is inside the gap formed by $m = 2$ and $m = 3$ mode coupling. As seen from Fig. 3 the frequency starts from the lower bound of the TAE gap and keeps constant in time for 10–20 ms. Then, it is chirped up to the upper bound of the TAE gap in less than 10 ms. In this case, the TAE frequency intersects the Alfvén continua in the edge region $\rho \sim 0.6$–0.9. The TAE may have a character of core-localized type mode, as observed in CHS. Note that the bursting TAEs propagate in the diamag-netic drift direction of energetic ion. This also supports that the chirping TAEs are excited by energetic beam ions.

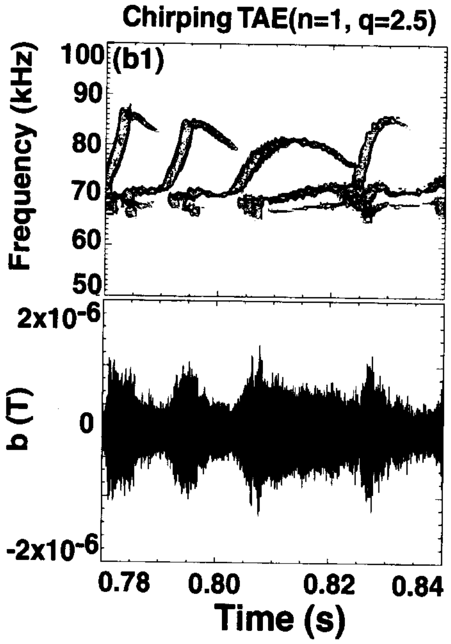

Fig. 3 Time evolution of the frequency and magnitude of the chirping TAE.

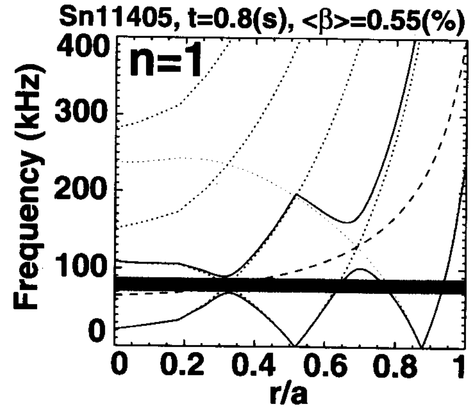

Fig. 4 Shear Alfvén spectra for $n = 1$ mode in the plasma shown in Fig. 3 where the chirping TAEs are observed. The hatched zone indicates the range of the observed frequency.

4. Fishbone-like Burst Modes

The other MHD instabilities other than TAEs are also observed in the same shot as shown in Fig. 3. The mode frequency is chirped very rapidly and the amplitude is modulated in time, similar to fishbone instabilities in a tokamak (Fig. 5). The mode numbers are $m = 2$ and $n = 1$. This $m = 2/n = 1$ fishbone-like burst mode (FB) appears in low electon density phase ($\bar{n}_e \leq 1.4 \times 10^{19}$ m^{-3}). The frequency of the burst mode is in the range of 20 ~ 60 kHz. The frequency of the burst mode is well below f_{TAE} correspondig to the TAE. The

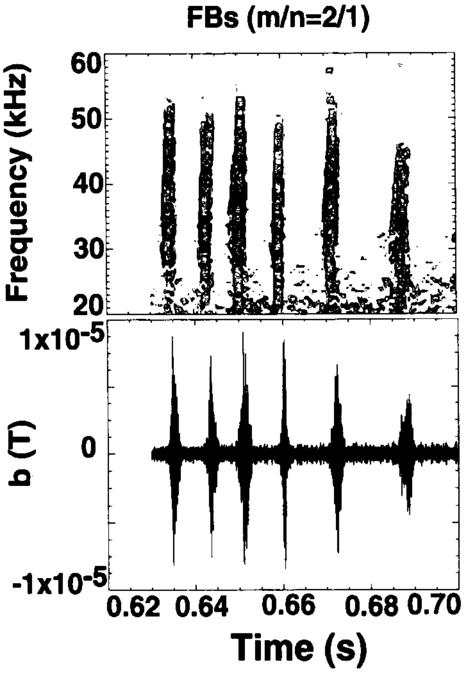

Fig. 5 Time evolution of the frequency and amplitude of $m = 2/n = 1$fishbone-like burst mode.

burst modes also propagate in the ion diamagnetic drift direction. The above burst modes is thought to be different from TAEs. The amplitude of the burst modes is about eight times larger than that of TAEs. In CHS experiments, similar fishbone-like burst modes with $m = 2/n = 1$ and $m = 3/n = 2$ are observed [4]. Although the burst modes observed in CHS slightly affect the bulk plasma confinement and energetic ions transport, those in LHD have no obvious effect on plasma performance.

5. Conclusion

The physics of energetic-ion-driven MHD instabilities is stud-ied in LHD. Two types of coherent magnetic fluctuations excited by the presence of energetic beam ions are observed only in NBI heated plasmas. One is TAEs, and the other the fishbone-like burst modes. TAEs with $n = 1$ and $n = 2$ are observed and their frequencies agree well with the TAE gap frequencies. The amplitude of TAEs is $\tilde{B}/B_t \sim 10^{-6}$ at the location of magnetic probe and corresponds to $\tilde{B}/B_t \sim 10^{-5}$ at the last closed flux surfaces. A new type $n = 1$ TAE are also observed. The mode frequency is chirped upward or downward within the TAE gap. The fishbone-like burst mode(FB) has $m = 2/n = 1$ mode structure. The burst modes also propagete in the ion diamagnetic direction. The amplitude of the burst modes is an order of magnitude larger than that of TAE, that is, $\sim 10^{-5}$ T at the location of the magnetic probe. The Chirping TAEs and FBs are ob-served in a few shots whose conditions are $R_{ax} = 3.6$ m, $B_t = 1.5$ T and heydrogen plasma. Excitation mechanisms of the chirping TAEs are not yet clarified and are left for a future study.

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