Energetic ion driven MHD instabilities and their impact on ion transport in Heliotron J plasmas

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Energetic ion driven MHD instabilities such as global Alfvén eigenmode (GAE) are observed in NBI-heated Heliotron J plasmas. In order to investigate the configuration effect on GAEs, we changed the magnetic configuration with regard to iota profile due to the variation of plasma current and coil current. The characteristics of observed GAEs are related to the iota profile and magnetic shear. The GAEs are excited by the sideband excitation. The bursting GAE might be effect on energetic ion transport because the some plasma parameters are simultaneously modulated with bursting GAEs.

Keywords: MHD instability, advanced stellarator, low magnetic shear, Alfvén eigenmodes, energetic ion transport.

1. Introduction

To clarify the MHD instabilities destabilized by energetic ions is important for the Deuterium-Tritium (D-T) fusion plasmas because the MHD instabilities could lead to the loss of alpha particles from confinement region before their thermalization and the ejected alpha particles might cause significant damage of first wall of a fusion device. Therefore, MHD instabilities destabilized by the energetic ions such as Alfvén eigenmodes (AEs) and energetic particle modes (EPMs) are being extensively studied in many stellarators/heliotrons as well as tokamaks using the Alfvénic ions produced by neutral beam injection (NBI), ion cyclotron resonance heating (ICRH) and D-T reactions.

The characteristics including the existence and the damping mechanisms of AEs such as continuum damping mainly depend on the structure of magnetic field. Toroidicity-induced AEs (TAEs), which can exist in the TAE frequency gap formed by the poloidal mode coupling m and m+1 (m: poloidal mode number) of shear Alfvén continua, are observed and effect on the energetic ion transport in the CHS [1] and LHD [2] with high and/or moderate magnetic shear. In the low shear stellarator/heliotron W7-AS [3] and Heliotron J [4], Global AEs (GAEs), which can exist on just below of upper continuum and above of lower shear Alfvén continuum are typically observed. Moreover helicity-induced AEs (HAEs), which are observed in W7-AS and LHD [5], can exist in the HAE frequency gaps formed by both toroidal and poloidal mode coupling. It will be more important AEs as well as GAEs in advanced stellarators with low toroidal field period N_f (e.g. N_f = 2~5) because AEs having the frequency comparable with ion diamagnetic frequency could have large growth rate and the frequency of HAE is scaled with the number of toroidal field period [6]. Therefore, it is important and of interest to investigate the GAEs and HAEs in the Heliotron J plasmas for advanced stellarator type fusion reactor with low magnetic shear and toroidal field period.

2. Configuration effect on global AEs

Heliotron J [7] is the helical-axis heliotron device with major and effective mirror radii R=1.2 m and $<a_{eff}>$=0.15~0.22 m, simultaneously. The magnetic configuration of Heliotron J is characterized by the low magnetic shear for the avoidance of the rational surface with low mode number and the combination of local quasi-isodynamic and bumpy (mirror) magnetic field for the good particle confinement. The Heliotron J plasmas are produced by the second harmonic electron cyclotron heating (ECH) with 70GHz, and can be additionally

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heated by the ECH, NBI and ICRF. We utilize the Alfvénic energetic ions produced by the tangentially co.- and counter-injected Hydrogen neutral beams with the energy of 24~27 keV for the destabilization of GAEs. The toroidal and poloidal magnetic probe array can determine the toroidal and poloidal mode number *n* and *m* of observed coherent MHD modes were installed on the vacuum vessel of Heliotron J.

In the NBI-heated Heliotron J plasmas, some GAEs with *m*=2/*n*=1 and *m*=4/*n*=2 are typically observed [4]. These modes propagate in the ion diamagnetic drift direction and of which frequency is correspond to that of discrete mode obtained from CAS3D3 [8] analysis where poloidal mode coupling are only taken into account. The magnetic fluctuation amplitudes of GAEs are in the order of $b_\theta/B_t \sim 10^{-6}$ at the position of the magnetic probes.

In order to investigate the configuration dependence on GAEs, we changed the magnetic configuration with regard to the differences of iota profiles. The plasma current and coil current can internally and externally vary the iota profile. In the plasma for AE excitation experiment, the plasma current consists of neutral beam driven current and bootstrap current. We changed the bumpy field in order to change the bootstrap current which is related to the confinement of trapped particle. The time evolution of amplitude of observed *m*=2/*n*=1 GAE and some plasma parameters are shown in Fig. 1, where the plasma beta obtained from diamagnetic loop, and line averaged electron density are almost same in the plasmas with different bumpy field. Both neutral beam driven and bootstrap currents flow in the co.-direction that increases the rotational transform. The differences of plasma current shown in Fig. 1 (d) are mainly resulted from the differences of bootstrap current. The amplitudes of observed *m*=2/*n*=1 GAEs are different in each magnetic configurations and is scaled with the amount of the plasma current.

In order to clarify the differences the amplitude of observed GAEs, We compared these observed frequencies at t = 0.26 s in each plasmas shown in Fig. 1 with shear Alfvén spectra that are calculated for equivalent two dimensional (2D) magnetic configuration

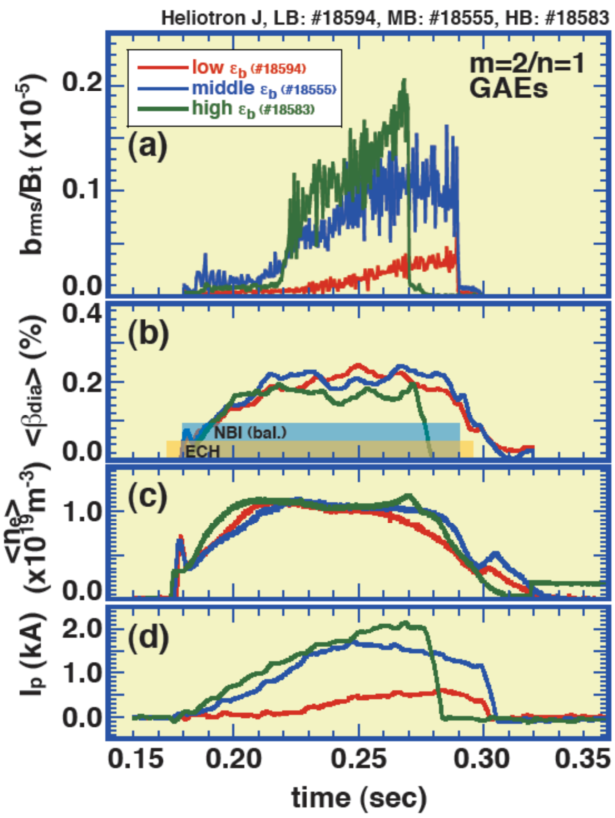

Fig. 1. Time evolution of (a) amplitude of observed m=2/n=1 GAEs, (b) plasma beta obtained from diamagnetic signals, (c) line averaged electron density and (d) plasma current.

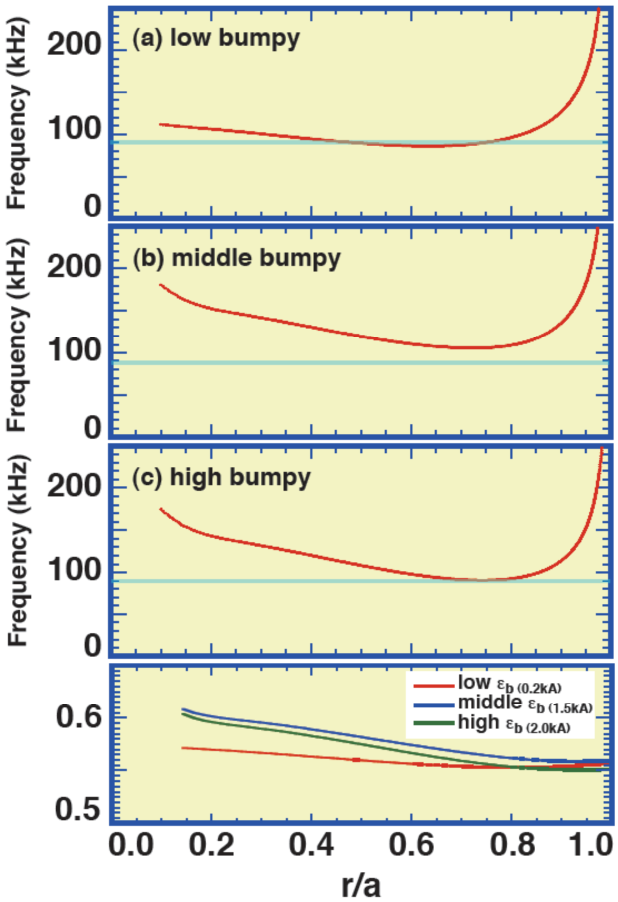

Fig. 2. Shear Alfvén spectra for n=1 for t = 0.26 s shown in Fig. 1 where poloidal mode coupling is taken into account. (a) Low bumpy case (b) middle bumpy case and (c) high bumpy case. (d) Profiles of rotational transform for each configuration.

where toroidal mode coupling is ignored. Shear Alfvén continua for n = 1 and profiles of rotational transform for the each configurations are shown in Fig. 2. In Fig. 2(a) ~ (c), red and blue lines denote the shear Alfvén continuum of $m = 2/n = 1$ and frequency of observed GAEs with $m = 2/n = 1$. As seen from Fig. 2, the observed mode frequencies lie just below the shear Alfvén continuum of $m = 2/n = 1$. The shear Alfvén spectra and rotational transform are almost same in each configurations in vacuum. The differences of shear Alfvén spectra shown in Fig. 2 (a) ~ (c) is caused by the plasma current including bootstrap current. The observed frequency does not clearly intersect the shear Alfvén continua, therefore, the GAEs would not be suffer from strong continuum damping. There are no differences in the electron and ion temperatures that indicates electron and ion Landau damping are same in each configuration. The bumpy field effects on the confinement of trapped particle, which cannot resonantly couple with the AEs. The reason of differences in observed GAEs amplitude might be explained by the differences of structure of GAEs. We need measurement of structure of observed GAEs and calculation of global mode analysis.

We also changed the iota profile due to the change of coil current shot by shot (named as iota scan experiment) and investigated the dependences of them on GAEs. In the iota scan experiments, we fixed the magnetic axis position and plasma volume and strength of bumpy field. The clear differences in amplitude of observed GAEs were not observed. The frequency of observed mode is related to the iota value.

3. Parametric studies of GAEs

AEs excited by the energetic ions will be destabilized when a certain threshold conditions are satisfied. The linear growth rate of AEs being proportional to the pressure gradient of energetic ions must be large enough to overcome the damping rate of the waves. Moreover, the velocity of energetic ions $v_{b//}$ is required to satisfy the resonance condition with the Alfvén wave. The GAE resonance condition for the fundamental excitation is $v_{b//}/v_A$ >1 and sideband excitation via the drift modulation of energetic ion orbit is $v_{b//}/v_A > k_{//(m,\ n)}\ /\ k_{//(m\pm1,\ n)} = [mi\text{-}n]/[(m\pm1)i\text{-}n]$. Here, $k_{//(m,\ n)}$ and $k_{//(m\pm1,\ n)}$ are the parallel wave number of waves, and i the rotational transform. The resonance condition for sideband excitation between m = 2 and $m = (2+1)/n = 1$ is $v_{b//}/v_A >$ 0.2. We investigated the resonance condition with $v_{b//}/v_A$ changing the electron density $\langle n_e\rangle$. The $m \sim 2/n = 1$ GAEs are destabilized in the condition of $v_{b//}/v_A \geq 0.25$ as shown in Fig. 3. The linear growth rate of AEs is related to the velocity ratio $v_{b//}/v_A$ as well as energetic ion beta $\langle\beta_{b//}\rangle$ and has a peak at unity. The fluctuation amplitude of observed GAEs increased with an increase in $v_{b//}/v_A$. These results of parametric study for $v_{b//}/v_A$ agree with the linear theory of AEs.

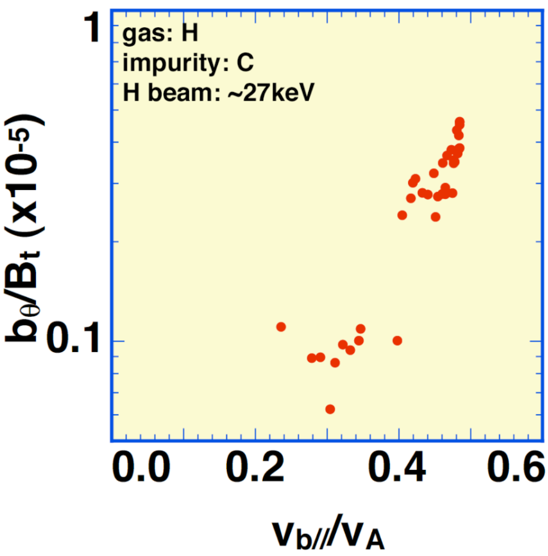

Fig. 3. The dependence of amplitude of observed m=2/n=1 GAEs against the ratio of energetic ion velocity and Alfvén velocity.

4. Energetic ion loss induced by the GAEs

In the plasma with magnetic configuration having the higher bumpy field, bursting GAEs ($m = 4/n = 2$), of which amplitude is two times larger than that of continuously observed GAEs are often observed, as shown in Fig. 4 (a)~(b). The frequency of bursting GAEs usually chirps down quickly. The time interval between each bursting GAEs increases with the increased in amplitude of bursting GAEs. This phenomenon can be explained by predator-prey model between energetic ion driven mode and energetic ions and might indicate the energetic ion transport induced by the energetic ion driven mode. The some plasma parameters such as H_α/D_α and, ion saturation current and plasma floating potential which are obtained from Langmuir probes located at outside last closed flux surface of plasma, are simultaneously increased with bursting GAEs, as shown in Fig. 4 (c)~(e). The increasing of ion saturation current is related to the increasing of amplitude of GAEs. Although the increasing in Langmuir probe signals cannot directly indicate the loss of energetic ion from the confinement region, the simultaneous increasing of the some plasma parameters indirectly indicates the energetic ion loss induced by the busting GAEs. The degradation of stored plasma energy induced by the bursting AEs observed in LHD and W7-AS were not observed in Heliotron J plasmas.

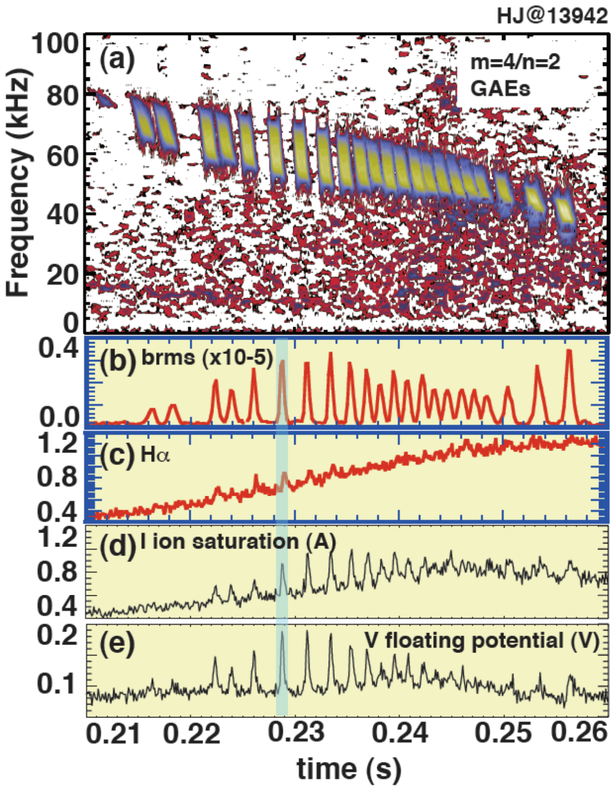

Fig. 4. Time evolution of (a) frequency spectrum and (b) amplitude of observed m=4/n=2 GAEs, (c) H_α/D_α signals, and (d) ion saturation current and floating potential obtained from Langmuir probes.

5. Conclusion

We investigated the dependence of magnetic configuration on GAEs using the variation of plasma current and coil current. In the high bumpy configuration, m=2/n=1 GAEs with the largest amplitude were observed. We compared with the observed frequencies and shear Alfvén spectra for n = 1. The differences of amplitude of observed GAEs in each configuration cannot be explained by the change of damping rate. GAEs were excited by the sideband excitation. The bursting GAEs with intense magnetic fluctuations might be affecting the energetic ion transport.

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