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Nonlinear Interaction between Alfvén Eigenmode and Geodesic Acoustic Mode Excited by Energetic Ions in the Large Helical Device

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1. Introduction

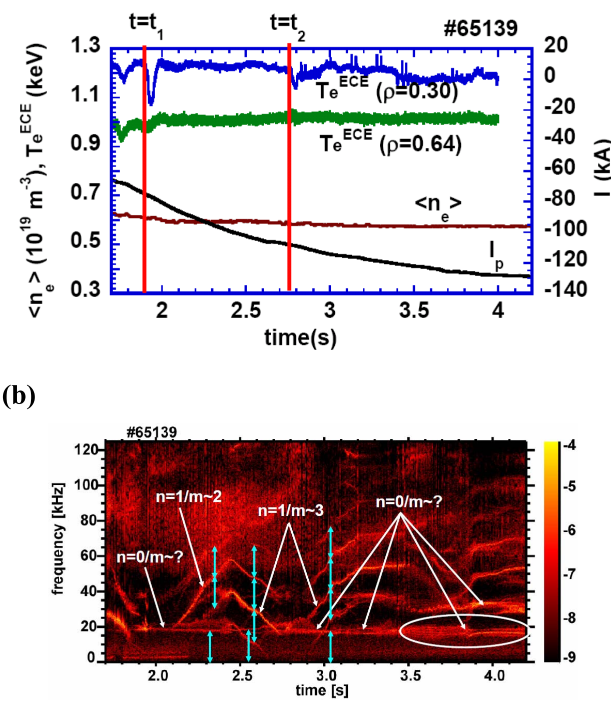
In a burning plasma, Alfvén eigenmodes (AEs) destabilized by energetic alpha particles may enhance radial transport and loss of them. In many tokamaks and stellarator/helical devices, characteristics of AEs and their impact on energetic ion transport are intensively investigated [1-5]. Recently, reversed shear AE (RSAE) or Alfvén cascade excited in a reversed magnetic shear (RS-) tokamak has received much attention [1,6-8], because the RS-configuration is a promising candidate for a steady-state and high performance operation in ITER[1]. It is interesting to investigate characteristics of AEs in stellarator/helical plasmas with RS-configuration. In the Large Helical Device (LHD), a RS- configuration has been realized by using intense counter neutral beam (NB) current drive, where the sign of the global magnetic shear changes positive to negative toward the plasma edge and is opposite to that in RS-tokamak.

2. Observation of Energetic Ion Driven Global Modes

A typical discharge waveform of a RS-plasma of LHD is shown in Fig.1(a), where the toroidal field is B_t=1.3T and the magnetic axis position of the vacuum field is R_{ax}=3.75m. The plasma current is driven up to ~140 kA by two counter NBI systems having about 2MW absorption power and about 180 keV hydrogen beams. The line averaged electron density is kept constant ($<n_e>\approx 0.6\times 10^{19}$ m^{-3}). Appreciable amount of neon is puffed into a plasma by a short pulse (~70ms) at t~0.8s to enhance NB power absorption and minimize electron return current in NB current drive, where the effective charge $Z_{eff}\sim 6$. Electron temperature profile is a parabolic shape having ~ 1.3 keV at the plasma center during constant $<n_e>$ phase. Electron density profile is considerably hollow, where $n_e(0)/n_{emax}$~0.5.

The rotational transform $\iota/2\pi$–profile measured by motional-stark-effect spectroscopy is non-monotonic. In the time window shown in Fig.1(a), the position of the minimum $\iota/2\pi$ moves inward from ρ~0.7 to ρ~0.4, and the minimum value gradually decreases, passing through the rational values $\iota/2\pi$=1/2 and 1/3. At these timings, electron temperature measured by electron cyclotron emission (ECE) T_e^{ECE} exhibits sharp drops at t=t_1 and t=t_2 in Fig.1(a). Figure 1(b) shows spectrograms of magnetic probe signal in this shot. Two types of coherent magnetic fluctuations up to ~100 kHz are clearly identified, where the ratio of the proton beam velocity to the Alfvén velocity is ~0.4 and the beam beta is estimated ~0.2%. One is a set of modes of which frequency chirps up or chirps down in about 0.3s, and the other is a mode with almost constant frequency (~18kHz). All the former modes have the same toroidal mode number n=1, and the latter has n=0. The fundamental n=1 mode indicated with an arrow in Fig.1(b) has the poloidal mode number m~2 in the phase of t~1.7 s to 2.4s, and m~3 in the phase of t > 2.5s. The m number of n=0 mode cannot be determined uniquely because of complex phase relation in a magnetic probe array. We have calculated cylindrical n=1 shear Alfvén (SA-)spectra using the experimentally obtained radial profiles of the rotational transform and electron density, taking into account impurity

(a)



(b)

Fig.1 (a) Typical waveform of a RS-plasma of LHD. T_e^{ECE} has sharp drops when the minimum of the rotational transform has passed the rational values 1/2(at t=t_1) and 1/3(at t=t_2)(vertical lines). (b) Spectrogram of magnetic probe signal. The length of vertical arrows is equal to the n=0 mode frequency. An ellipse indicates the splitting of n=0 mode spectrum.

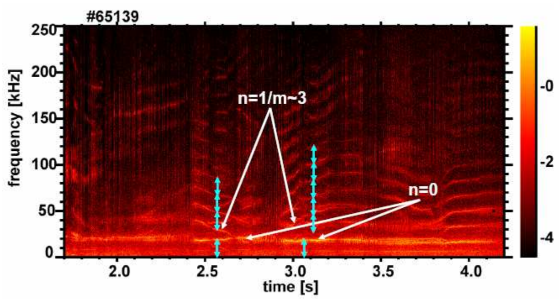
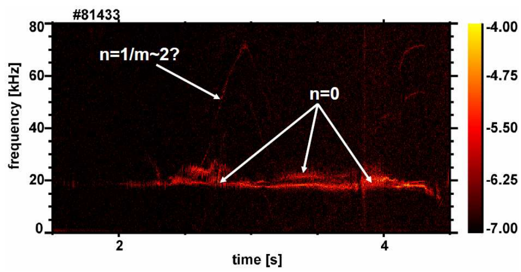


Fig.2 Spectrogram of microwave interferometry signal in a shot shown in Fig.1. The length of vertical arrows is equal to the n=0 mode frequency.

content. The TAE gap by m=2 and m=3 poloidal mode coupling is formed around ρ~0.7 and the gap frequency remains unchanged from t=1.3s to t=3.3s in a shot shown in Fig.1(a). The minimum of the m/n=3/1 SA-continuum decreases substantially from the TAE frequency down to 0 kHz at t~2.8s. Then, the maximum of the m/n=3/1 continuum increases from 0 kHz at t~2.8s to ~40 kHz at t=3.2s. This time evolution agrees well with that of the observed m~3/n=1 fundamental mode indicated with an arrow in Fig.1(b), except around t~2.8s. That is, the frequency reaches the minimum value of ~20 kHz at t~2.8s, instead of 0 kHz. The minimum value is close to the geodesic acoustic mode frequency [9] evaluated including energetic ion pressure. The above-mentioned frequency sweeping bounded by the geodesic curvature effect agrees well with the theory developed for RS-tokamak [10]. In conclusion, the n=1 frequency-sweeping mode is RSAE excited by energetic ions and is observed for the first time in a stellarator/helical plasma. So far, the observed RSAE frequency is always swept downward and then upward, in contrast to rare observation of the downward sweeping in tokamak RSAE [10]. On the other hand, the frequency of n=0 mode corresponds to the GAM frequency. This mode is thought to be GAM excited by energetic ions, and will be the same as n=0 mode observed in JET [11]. These RSAE and GAM are also detected with microwave interferometry as shown in Fig.2. Recently, potential fluctuations $\delta\phi$ of these modes were detected by heavy ion beam probe (Fig.3). The amplitude reaches very high level, ~0.9 kV, which is comparable to electron temperature. Information of radial structures of these modes was obtained by correlation analysis of ECE and soft X-ray signals with magnetic probe signal. The coherence has a peak at ρ~0.4 for both n=1 RSAE and n=0 GAM (Fig.4). This figure indicates that n=1 mode location agrees well with the location of RSAE.

(a)



(b)

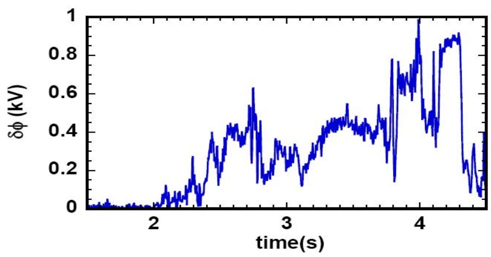


Fig.3 (a) Spectrogram of potential fluctuations measured by heavy ion beam probe. (b) Time evolution of the amplitude of n=0 potential fluctuations filtered from f=10 kHz to 30kHz

3. Nonlinear Interaction between RSAE and GAM Driven by Energetic Ions

As seen from Figs. 1 and 2, a lot of satellites of n=1 RSAE are excited by nonlinear interaction between n=1 RSAE and GAM (with n=0). At t=2.55s in Fig.1(b), for instance, nonlinear interaction between the fundamental n=1 RSAE (with m~3) of f=31 kHz(=f_1; n=n_1) and n=0 GAM of f=19kHz(=f_0; n=n_0) generates two modes through addition and subtraction of these frequencies: n=1 mode of f=50 kHz(=f_2; n=n_2) and that of f=12 kHz(=f_{-1}; n=n_{-1}). The following selection rule for the mode frequency is satisfied among these modes, that is, $f_1+f_o=f_2$ and $f_1-f_0=f_{-1}$. The other selection rule for the toroidal mode number is easily satisfied because n_0=0, that is, $n_1+n_0=n_2$ and $n_1-n_0=n_{-1}$. Moreover, the n=1 driven modes interacts with GAM further and generates a multitude of RSAE, as seen from Fig.1(b) and Fig.2. The bi-coherence analysis also confirmed the nonlinear coupling.

3. Conclusion

RSAE with n=1 and GAM with n=0 which are excited by energetic ions were identified for the first time in a helical plasma with RS-configuration. It is also observed for the first time that nonlinear interaction between n=1 RSAE and n=0 GAM generates a lot of satellites of RSAE.

Acknowledgements

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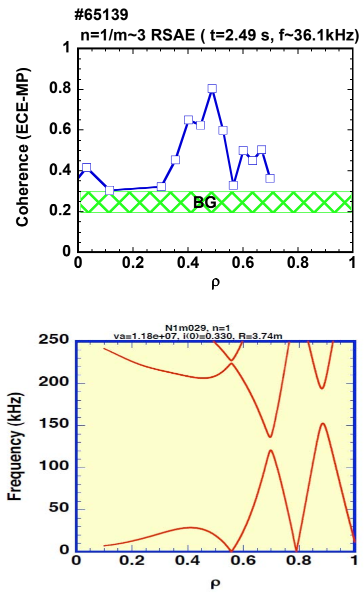
References

[1] A. Fasoli et al., Nucl. Fusion **47**, S264 (2007).
[2] K. Toi et al., Nucl. Fusion **40**, 1349 (2000).
[3] A. Weller et al., Phys. Plasmas **8**, 931(2001).
[4] K. Toi et al., Plasma Phys. Control. Fusion **46**, S1 (2004)
[5] S. Yamamoto et al., Nucl. Fusion **45**, 326 (2005).
[6] H.L. Berk et al., Phys. Rev. Lett. **87**, 185002(2001).
[7] S.E. Sharapov et al., Phys. Plasmas **9**, 2027 (2002).
[8] M. Takechi et al., Phys. Plasmas **12**, 082509 (2005).
[9] N. Winsor et al., Phys. Fluids **11**, 2448 (1968).
[10] B.N. Breizman et al., Phys. Plasmas **12**, 112506 (2005).
[11] H.L. Berk et al., Nucl. Fusion **46**, S888 (2006).

(a)



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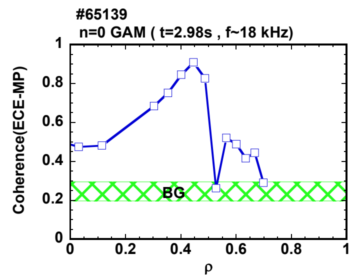

Fig.4 Radial profiles of the coherence between ECE signal and MP signal for RSAE (a) and GAM (b). In Fig.4(a), Shear Alfvén spectrum is also shown. “BG” stands for the noise level.