The first observations of beta-induced Alfvén eigenmodes in edge remnant magnetic island on J-TEXT

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Introduction

Alfvén eigenmodes (AEs), such as toroidal AEs (TAEs) and beta-induced AEs (BAEs) are observed in various tokamaks and stellarators. BAEs are the eigenmodes situated in the low frequency gap in the Alfvén continuum, and are formed by the coupling of the shear-Alfvén wave with the compressional response of the plasma induced by the geodesic curvature of the equilibrium magnetic field and plasma pressure. BAE can be driven by the energetic particles (EPs) and in turn resonantly interact with them, which would result in the redistribution and loss of EPs [1] and thereby lead to degrading the plasma performance and even damage reactor's first wall. Recently, many observations have shown that BAEs can exist with magnetic island in the absence of EPs [2-3]. Many experimental and theoretical investigations as well as numerical simulations try to understand the physics of BAE with magnetic island, but the properties of BAE still remain a topic of research due to many open questions such as the excitations of BAE in the presence of the magnetic island. Additionally, Simulation results predict that BAE could be unstable in ITER [4], so understanding their stability is critical.

Recently, the experimental attempt on the island divertor configuration is performed on J-TEXT using the m/n=3/1 resonant magnetic perturbation (RMP) [5]. In this work, the description of the dynamic characteristics of BAE during the transition from limiter configuration to island divertor is presented. The magnetic perturbations here are measured by two sets of Mirnov probes array (poloidal array and toroidal array) [6].

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Characteristics of BAEs with 3/1 edge closure magnetic island

Figure 1 shows the typical experimental observations of BAEs in two discharges 1056894 (red) and 1056902 (blue). They share same RMP connections but different RMP currents. First focusing on the discharge 1056894 with I_p = 150 kA, B_t = 1.4 T and edge safety factor q_a = 3.2, the RMP coil current is applied at 0.26s and ramps up to the flattop of 4 kA at about 0.29s (figure 1(c)). The field penetration occurs at around 0.27s indicated by the jump of the measured radial magnetic field B_r (purple line). An edge m/n = 3/1 magnetic island is generated at this moment. The edge toroidal rotation at r = 22 cm increases from 0 to 8 km/s in the co-Ip direction (figure 1(d)). Meanwhile, a mode with frequency of around 30 kHz is observed in the spectrogram of Mirnov signal (figure 1(e)). Figure 2 illustrates the cross-phase and amplitude from the signals of toroidal (left) and poloidal (right) Mirnov probes array in the BAE frequency range. The bottom row plots the corresponding vacuum Poincaré plots on the toroidal section $\theta_{pol} = -45^o$ and poloidal section $\emptyset_{tor} = 56.25^o$, at which the Mirnov probe arrays are installed. Here, the Poincaré plots are calculated by a simple modelling, which is done using the equilibrium field calculated from the EFIT code plus the perturbation fields from the RMP coils. The cross-phases jump by 180^o around two toroidal angles of $\emptyset_{tor} = 22.5^o$ and 202.5^o and six poloidal angles of $\theta_{pol} = 22.5^o$, 97.5^o, 157.5^o, 195^o, 247.5^o and 300^o, where the amplitudes show a minimum. The mode shows a standing wave structure and has the same helicity of m/n = 3/1 magnetic island. Comparing with the Poincaré plots, it can be clearly seen that the nodes of this mode are located at O- and X-point of the magnetic island.

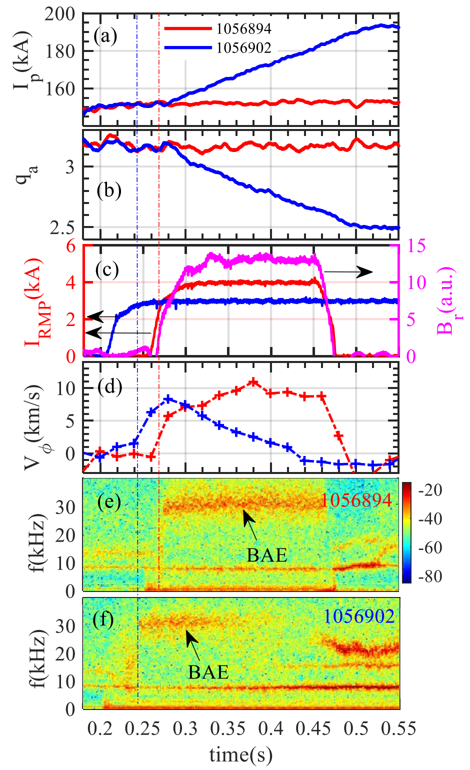

figure 1. Time evolution of the main parameters for two discharges 105894 (red) and 1056902 (blue). (a) plasma current, (b) edge safety factor, (c) RMP current, (d) toroidal rotation of CV, (e) and (f) spectrogram of the Mirnov signal.

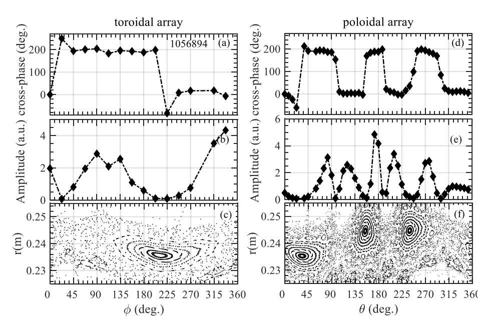

Figure 2. (a) and (d) cross-phase, (b) and (e) amplitude in the BAE frequency range from the signals of toroidal (left) and poloidal (right) Mirnov probes arrays. (c) and (f) the corresponding vacuum Poincaré plots.

These characteristics conform to the previous observations of BAE on J-TEXT [7-8].

Dynamics of BAEs during the process of the opening of edge 3/1 magnetic island

In discharge 1056902, 3 kA RMP current is applied. The RMP penetration happens at 0.255s indicated by the increase of toroidal rotation in the co-I_p direction. The ramp-up plasma current I_p is set to reduce the edge safety factor q_a. As q_a decreases, the q = 3 rational surface moves outwards, and the edge 3/1 magnetic island is gradually opened by the interactions with the poloidally localized limiter, thereby forming the island divertor configuration. In this process, both the toroidal rotation and the amplitude of BAE decrease gradually. Finally, the BAE disappears at about 0.4s (I_p = 170 kA) while the toroidal velocity keeps constant again at about 0.44s (I_p = 180 kA). More experimental evidences aren't given here, but the corresponding vacuum Poincaré plots for different plasma current I_p = 160 kA, 164 kA and 170 kA given in figure 3 can clearly provide the facts that the edge 3/1 magnetic island are opened and the island divertor configuration is successfully carried out on J-TEXT tokamak.

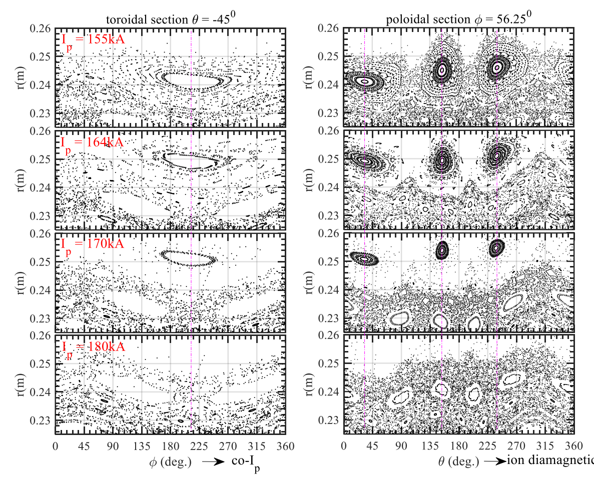

Figure 3. The corresponding vacuum Poincaré plots for different plasma current I_p = 160 kA, 164 kA, 170 kA and 180 kA.

From figure 4, the dynamics of edge 3/1 magnetic island is clearly observed. Outward shifted magnetic islands are found in three cases of I_p =160 kA, 164 kA and 170 kA, and the remnant islands become smaller and smaller. Additionally, the 3/1 magnetic island has a very small shift towards co-I_p and electron diamagnetic directions with the increasing I_p, which can be negligible compared to the space resolution of the Mirnov arrays. Figure 4 shows the detailed time evolution of BAE during the process of the opening of edge 3/1 magnetic island. The BAE still exists in the opening magnetic island but its amplitude decreases continuously with time. Notice

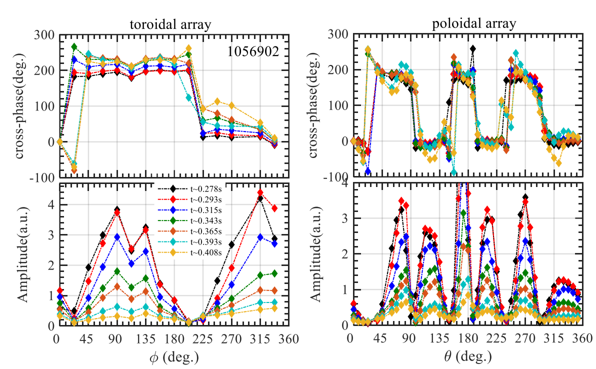

Figure 4. (a) and (d) cross-phase, (b) and (e) amplitude in the BAE frequency range from the signals of toroidal (left) and poloidal (right) Mirnov probes arrays. (c) and (f) the vacuum Poincaré plots.

that for the poloidal Mirnov array, the strength of BAE is consistently weaker at the beginning and during the process at the low field side (LFS) with the $\theta = 0^o - 90^o$ and $270^o - 360^o$. Experimental results have proved that the strength of BAE is related to the size of magnetic island, that is, the larger the magnetic island, the stronger the BAE [8]. A narrow magnetic island at the LCFS may be the possible explanation for the weaker BAE. In addition, focusing on the cross-phases, they aren't showing nearly constant phase in the space between two nodes after t ~ 0.27s, especially around the nodes of $\emptyset_{tor} = 202.5^o$ and $\theta_{pol} = 22.5^o, 157.5^o,\ 247.5^o$ and $300^o,$ where the strength of BAE becomes very small. Interestingly, most of these nodes are around the O-point of magnetic island. These results indicate that when the q_a decreases to a certain value, the BAE signal begins to disappear from the Mirnov probes located around the nodes, especially the ones located round the O-point.

Conclusions

The dynamics of the BAE during the opening of edge 3/1 magnetic island is investigated on the J-TEXT tokamak. BAE is found to still exist in the remnant island but its amplitude decreases as the width of the remnant island becomes smaller. These results help to understand the relationship between magnetic island and BAE, thereby possibly having implications for the excitation mechanisms of BAE.

Acknowledgements

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References

[1] Chen, L., and Fulvio Zonca. *Rev. Mod. Phys.* 88.1, 015008 (2016).

[2] Buratti, P., *et al*. *Nucl. Fusion* 45.11: 1446 (2005).

[3] Chen, W., *et al*. *Nucl. Fusion* 51.6: 063010 (2011).

[4] Todo, Yasushi, and Andreas Bierwage. *Plasma Fusion Res.* 9: 3403068-3403068 (2014).

[5] Rao, B., *et al*. *Fusion Eng. Des.* 89.4: 378-384 (2014).

[6] Guo, D., *et al*. *Rev. Sci. Instrum.* 88.12: 123502 (2017).

[7] Liu, L., *et al*. *Plasma Phys. Control. Fusion* 57.6: 065007 (2015).

[8] Liu, L., *et al*. *Nucl. Fusion* 59.12: 126022 (2019).