EXPERIMENTAL STUDY OF EPM INSTABILITY IN THE EAST OFF-AXIS REGION WITH ELEVATED SAFETY FACTOR (Q) VALUE

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A comprehensive set of discharge conditions characterized by weak or reversed magnetic shear has been meticulously established on the Experimental Advanced Superconducting Tokamak (EAST). In these configurations, the minimum safety factor, denoted as q_0 or q_{min}, is approximated to be 2. This configuration is achieved by employing the lower hybrid current drive (LHCD) or by leveraging the synergistic effects of electron cyclotron resonance heating (ECRH) in conjunction with LHCD. The radial position of q_{min} is strategically positioned to a range of $1.98 \leq R \leq 2.1m$ ($R_0 \leq 1.9m$), corresponding to a normalized minor radius of $0.2 \leq \rho \leq 0.5$. The reversed magnetic shear configuration is easily captured by the excitation of Reversed Shear Alfvén Eigenmodes (RSAEs) [1,2] and double tearing modes (DTMs) [3,4], and the target of $q_{min} \approx 2$ is readily reconstructed using the combined data from the Polarimeter Interferometer (POINT) and edge magnetic pickup diagnostics.

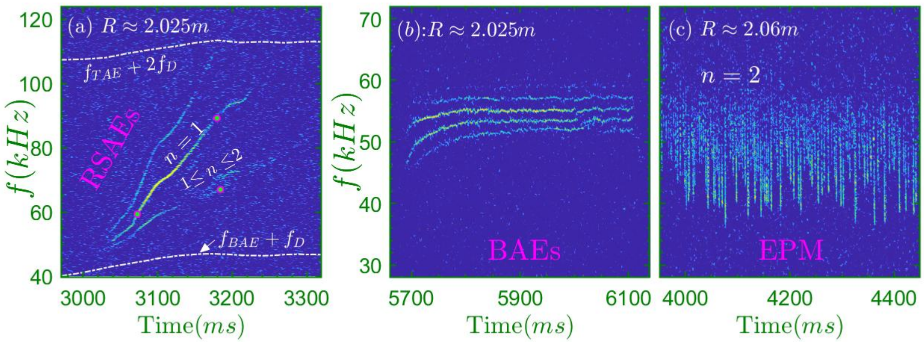

Fig.1. Three distinct types of fast-ion instabilities have been observed on EAST: (a) RSAEs, (b) BAEs and (c) EPM instability.

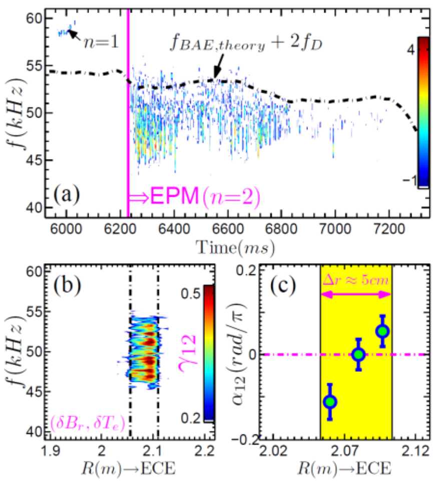

Fig.2. The radial structure of EPM instability is demonstrated by the ECE diagnostic.

Three distinct types fast-ion instabilities, namely RSAEs, beta-induced Alfvén Eigenmodes (BAEs), and energetic particle mode (EPM), are easily observed at the off-axis region as shown in Fig.1. On the EAST tokamak, pairs of BAEs and RSAEs instabilities are found to coexist within a similar radial region. Moreover, it is observed that the BAEs can readily transition into RSAEs as the safety factor profile (q-profile) undergoes changes. The fast-ion population contributing to the excitation of both BAEs and RSAEs are nearly equivalent. However, the thermal pressure gradient associated with the excitation of BAEs is greater than that for RSAEs. The radial location of EPM is situated further outward compared to the pairs of BAEs and RSAEs. Intriguingly, the fast-ion population exhibits a marked increase following RSAEs excitation, likely due to nonlinear redistribution processes that transiently enhance trapped particle orbits. In contrast, EPM instabilities require a significantly higher fast-ion density threshold compared to BAEs modes, reflecting their distinct resonance dependencies on energetic particle gradients.

Fig.2. illustrates the coupling between EPM and BAE instabilities, along with the spatial structure of the EPM mode. The EPM exhibits a downward frequency sweep originating from the BAE spectral gap, with a sweep duration of $\Delta t \leq 0.5\,ms$ and a total frequency shift of $\Delta f \leq 10kHz$. The mode is radially localized between $2.05 \leq R \leq 2.1m$ (corresponding to the normalized radius $0.4 < \rho \leq 0.5$), and its radial phase angle increases by $\Delta\alpha_{12} \approx 0.2\pi\, rad$ from the inner to outer regions. Notably, under specific magnetic shear condition, a triangle eigenmode structure of EPM is observed, which enhances thermal particle confinement by suppressing turbulent transport through poloidal flow shear modulation.

Fig. 3. quantifies the interplay between fast-ion density (probed via neutron yield S_n), EPM instability excitation thresholds, and the normalized thermal ion temperature gradient (R/L_{T_i}). A rapid rise in neutron yield S_n (indicating fast-ion accumulation) at $t = 2.52s$ triggers EPM onset, followed by a delayed increase in R/L_{T_i} ($t \geq 2.52s$). This sequence suggests the possible of EPM-induced zonal flow shear modulates turbulent transport, leading to ion temperature profile stiffening. Consequently, the self-regulated coupling between fast-ion-driven instabilities and thermal transport enhances overall plasma confinement, as evidenced by the synergistic evolution of S_n and R/L_{T_i}. As indicated in Fig. 4. The recently commissioned Imaging Neutral Particle Analyzer (INPA) [5] diagnostic is employed to resolve the velocity-space dynamics of fast ions during fishbone instability excitation. By capturing pitch-angle and energy-resolved neutral particle fluxes, INPA reveals transient fast-ion redistribution ($\Delta\beta_{fast} \geq 10\%$) correlated with nonlinear mode evolution, providing direct evidence of phase-space transport driven by resonant wave-particle interactions.

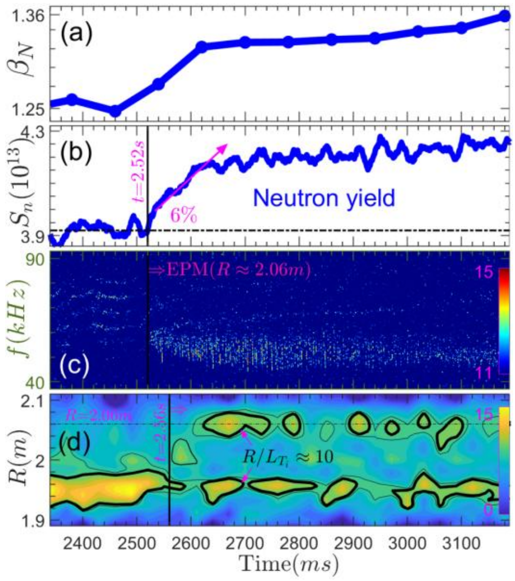

Fig.3. The interplay between fast-ion density (probed via neutron yield S_n), EPM instability excitation thresholds, and the normalized thermal ion temperature gradient (R/L_{T_i}).

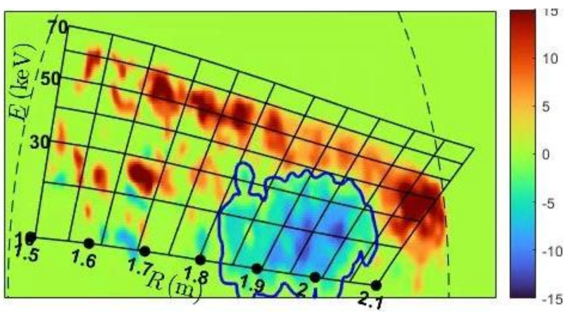

Fig.4. Exploring the Correlation between Fishbone Instability and the Redistribution of Fast Ions in Phase Space, as Measured by the Newly Developed INPA Diagnostic.

REFERENCES

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