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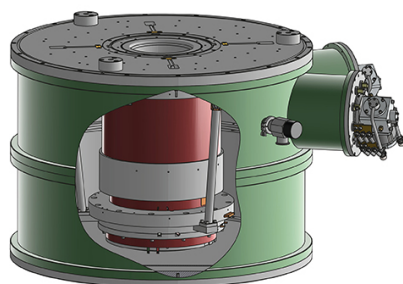


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Characteristics of core beta-induced Alfvén eigenmodes with shear flow in EAST NBI heating plasmas

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Abstract

The basic features and relationship with zonal flows of multiple branches of beta-induced Alfvén eigenmodes (BAEs) are investigated in the EAST tokamak. Those branches of BAEs, excited by tangentially injected neutral beam injection, are located in the central region ($0.2 \leq \rho \leq 0.4$), with frequencies in the range of $50 \leq f \leq 70$ kHz and low toroidal mode numbers $1 \leq n \leq 5$. The excitation of BAEs is clearly characterized by three typical features: an increase in the $\omega_{E \times B}$ shear locally, accompanied by simultaneous rises in both central rotation velocity and electron temperature. Radial profiles of the mode phase angle from electron cyclotron emission (ECE) diagnostics vary significantly with n . Global gyrokinetic simulations of core BAEs are performed in both linear and nonlinear regimes. In the linear regime, the unstable BAE branches are consistent with experiment on toroidal mode number, real frequency and the mode structure phase angle. The radial variation of BAE phase angle is primarily caused by bulk plasma kinetic effects rather than the energetic particle (EP) non-perturbative drive. In the nonlinear regime, single- n BAE without zonal fields saturates at a large amplitude that triggers the non-adiabatic frequency chirping on a fast timescale of sub-millisecond, while the self-organized zonal flow beat-driven by BAE greatly reduces BAE saturation amplitude below the chirping threshold, which is in consistency with experimental observation. Moreover, it is confirmed that the criterion of zonal flow regulation on dissipative-type instability (such as AEs) becomes $\omega_{E \times B} > \omega_r$ rather than traditional $\omega_{E \times B} > \gamma_L$ for reactive-type instability. In general,

^a see Gong *et al* 2024 (<https://doi.org/10.1088/1741-4326/ad4270>) for the EAST Team.

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the self-organized zonal flow can improve plasma confinement through regulating both BAEs and drift-wave turbulence.

Keywords: beta-induced Alfvén eigenmode, phase angle, zonal flow, EAST tokamak

(Some figures may appear in colour only in the online journal)

1. Introduction

In magnetically confined fusion devices, the destabilization of shear Alfvén waves (SAWs) by energetic particles (EPs)—including both fusion-born alpha particles and energetic ions/electrons from auxiliary heating—poses a critical challenge for plasma energy confinement. Through resonant wave-particle interactions, the marginal stable Alfvén eigenmodes (AEs), such as the toroidal Alfvén eigenmode (TAE) [1, 2], reversed shear Alfvén eigenmode (RSAE) [3] and beta-induced Alfvén eigenmode (BAE) [4] can be excited by the free energy of EPs. These unstable AEs can, in turn, lead to enhanced EP transport and the decrease of heating efficiency, potentially degrading plasma confinement and damaging the first wall [5, 6]. Therefore, understanding various linear and nonlinear characteristics of AE is necessary for burning plasma control in fusion reactors.

Among these AEs, the BAE arises from plasma compressibility due to geodesic effect [7]. The BAE can interact with both thermal ions and EPs, since it oscillates with the geodesic acoustic mode (GAM) frequency, which is close to the thermal ion transit frequency and EP precessional drift frequency [8]. The BAE is identified experimentally in DIII-D neutral beam injection (NBI) heated plasma for the first time [9]. Then it has been widely observed in other tokamaks, such as TFTR [10, 11], ASDEX Upgrade [12], KSTAR [13] and HL-2A [14]. In recent Experimental Advanced Superconducting Tokamak (EAST) campaign, BAEs have been systematically investigated under various conditions. The BAEs are firstly excited by magnetic islands [15], by energetic electrons [16, 17], and by runaway electrons [18]. Later on, BAE activity has been reported during sawtooth-like oscillations in mixed heating scenarios [19, 20], as well as in NBI-heated discharges with vertical injection under low-collisionality, high- T_i conditions, where multi-scale instabilities including BAEs were observed [21].

Many theoretical and simulation efforts have been performed to understand the linear properties and nonlinear evolution of BAEs. The general fishbone-like dispersion relation (GFLDR) is developed as a powerful theory tool that obtains BAE dispersion relation based on first-principle gyrokinetic approach [8]. The LIGKA gyrokinetic eigenvalue simulation shows that the BAE continuum accumulation point can be shifted by the diamagnetic effects, elongation and trapped particles [12]. Moreover, the BAE is also studied using gyrokinetic and kinetic-MHD hybrid simulations based on initial value problem approach. Specifically, the linear dispersion relation and nonlinear frequency chirping of BAE are successfully reproduced by XHMGC [22–24] and GTC [25–31]. The effect of the electron redistribution on the nonlinear saturation

of BAE [32], and the interaction between BAE and ITG turbulence are explored by ORB5 [33, 34]. The BAE control by off-axis EP redistribution is shown by M3D-K [35].

Beyond the wave-particle interactions, the nonlinear process of wave-wave coupling is also crucial for AE problems. Recent JET Deuterium-Tritium experiments observe that: multi- n Alfvénic modes can nonlinearly generate zero-frequency fluctuations, which in turn enhance core plasma confinement through shear flow effects [36].

In this work, we report the linear and nonlinear features of multi- n BAE branches in EAST discharge #61 970, which are excited by tangentially injected NBI. Based on experimental diagnoses, each BAE remains its frequency unchanged during the NBI injection, and the frequency difference is fixed small between different toroidal mode n numbers. The phase angle of BAE mode structure exhibits a clearly radial dependence that varies between different n numbers, and both the radial electric field amplitude $|E_r|$ and corresponding $E \times B$ shearing rate $\omega_{E \times B}$ in the core plasma are amplified by these BAEs. Global gyrokinetic simulations are then carried out to explain the underlying mechanisms of experimental observations, which successfully reproduce the physics process of BAE linear excitation with electromagnetic polarization and radial phase variation, and then investigate the nonlinear processes of non-adiabatic frequency chirping and beat-driven of zonal fields, resulting in different saturation amplitudes. In general, our current work provides physics pictures for the novel observations of BAE linear and nonlinear behaviors in EAST NBI-heated plasmas, which evolves both the bulk plasma and EP kinetic effects, and clarifies the importance of nonlinear wave-particle resonance and wave-wave coupling in different regimes. The remainder of this work is organized as follows. Section 2 reports the EAST experimental setup and observation of BAE and enhancement of radial electric field. Section 3 presents the GTC simulation results of linear BAE properties. Section 4 presents the BAE nonlinear simulations with and without keeping zonal fields, clarifying the nonlinear saturation mechanism and the generation of radial electric field. The summary is given in section 5.

2. Experimental setup and results

The experiment was conducted in the EAST, which has a major radius of $R \leq 1.9$ m and a minor radius of $a \approx 0.45$ m. An upper single null (USN) magnetic configuration was adopted, featuring an elongation of $\kappa \approx 1.65$ at last closed flux surface (LCFS) and a plasma cross-sectional area of approximately 0.98 m^2 . The positive direction is defined as anti-clockwise from the top view as shown in figure 1(a). The

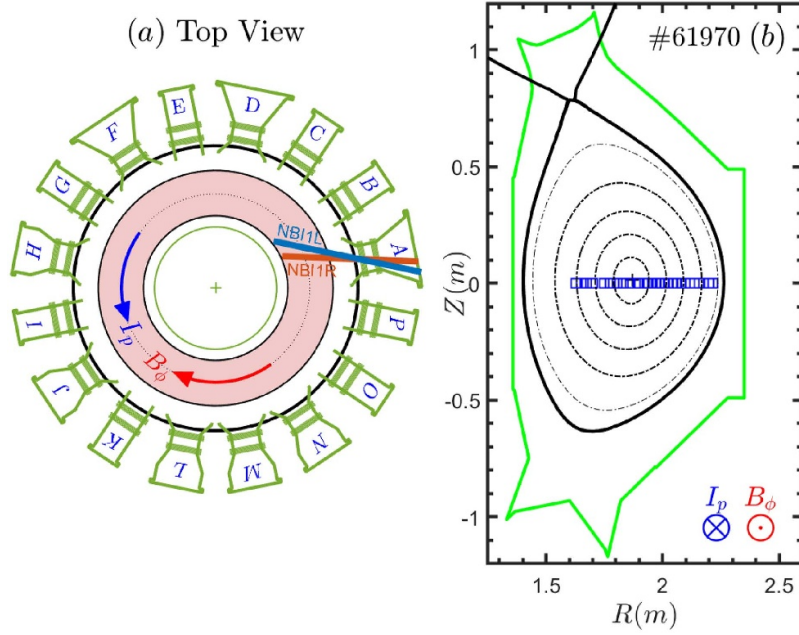


Figure 1. EAST layout and discharge magnetic configuration for the shot #61970. *Note:* the reconstructed magnetic axis is estimated as $R_0 \leq 1.9$ m, and the radial coverage of ECE array is marked by the blue squares in (b).

key plasma parameters for the shot #61970 are as follows: a core line-integrated electron density of $n_{10^9} \approx 3 \times 10^{19} \text{ m}^{-3}$, plasma current $I_p = 0.4$ MA, toroidal magnetic field in the negative direction with $|B_\phi| \cdot R \approx 4.16 \text{ T} \cdot \text{m}$, safety factor at the 95% magnetic surface is $q_{95} \approx 6.5$, and plasma internal inductance is $l_i \approx 1.11$. By combining data from the POLarimeter-INTERferometer (POINT) and edge magnetic pickup diagnostics, the reversed q -profile with $q_{\min} \leq 2$ is reconstructed. As shown in figure 1(b), the characteristic fluctuations of these BAEs are well-resolved by the electron cyclotron emission (ECE) system, which provides local measurements.

The reversed magnetic shear configuration is established using a combination of lower hybrid current driven (LHCD) and off-axis electron cyclotron resonance heating (ECRH), with powers of $P_{\text{LH}} \approx 3.8$ MW and $P_{\text{EC}} \approx 0.45$ MW respectively. Usually, the $m/n = 2/1$ double tearing mode (DTM) is excited at such conditions, accompanied by the collapse event [37, 38], where the m and n are the poloidal and toroidal mode numbers respectively. Fast ions are primarily generated by NBI with a source power of $P_{\text{NB}} \approx 1.7$ MW and a beam energy of $E_B \approx 57$ keV. The NBI system at Port A comprises two beam lines, NBI1L (tangential) and NBI1R (perpendicular), both situated on the EAST midplane. Their tangential radii (defined as the perpendicular distance from the beam line to the device axisymmetric axis) are $R_{\text{tan1}} \approx 1.26$ m and $R_{\text{tan2}} \approx 0.73$ m. The beams intersect at an angle of $\alpha \approx 8.7^\circ$ and are injected in the co-current direction, as shown in figure 1(a). The resulting beam ions are sub-Alfvénic, with a maximum velocity of $v_{B,\text{max}}/v_A \sim 0.3$. Based on a classic fast-ion distribution model, the pitch angles ($v_{\parallel}/v$) for the two beams are estimated as $v_{\parallel}/v \approx 0.38$ for NBI1R and $v_{\parallel} \approx 0.65$ for NBI1L [39].

The BAEs instability is excited by the injection of NBI1L, and the features of these modes are shown in figure 2. Five distinct branches are observed in the frequency range of $50 \leq f \leq 70$ kHz. The observed upward frequency sweep is attributed to a change in the Doppler shift, with a frequency of approximately $f_D \approx 4$ kHz. Analysis of the coherence (γ_{12}) between core soft x-ray and ECE signal reveals that those BAEs are detected in specific ECE channels, characterized by $\gamma_{12} \geq 0.4$. As shown in figure 2(b), these branches exhibit their maximum radial extent in the range $1.99 \leq R \leq 2.07$ m, corresponding to a normalized minor radius of $0.2 \leq \rho \leq 0.4$. The peak coherence of $\gamma_{12}|_{\text{max}} \approx 0.8$ is observed at $R \approx 2.025$ m for the branch (f_2). In figure 2(c), the radial phase angles for the different frequency branches ($f_1, f_2, \dots, f_5$) are marked using different colors. The cross-phase angle for the higher BAE frequency branches (f_2, f_3, f_4 and f_5) decrease with major radius. There are two possible interpretations: either (i) the mode propagates radially outward with a wave number $k_r = \Delta\alpha_{12}/\Delta r$, or (ii) the mode possesses an ‘boomerang’ structure characterized by a specific radial phase gradient, $d\alpha_{12}/dr$.

Although the radial coverage of the three frequency branches (f_1, f_2 and f_3) is similar, their radial phase structures differ significantly, as illustrated in figure 2(c). Over a radial distance of $\Delta r \approx 8$ cm, the total phase shifts $\Delta\alpha_{12} \approx 0, 0.25\pi$ and 0.6π for f_1, f_2 and f_3 respectively, with the phase referenced to $\alpha_{12} = 0$ at $R \approx 2.06$ m. Interestingly, the radial extent of the two higher frequency branches, f_4 and f_5 , is located in the outer region of $2.025 \leq R \leq 2.07$ m, implying that modes with higher toroidal mode numbers are subject to stronger damping in the core region ($R \leq 2.025$ m).

The toroidal mode numbers for these BAE branches could not be detected by the edge magnetic pickup array in shot

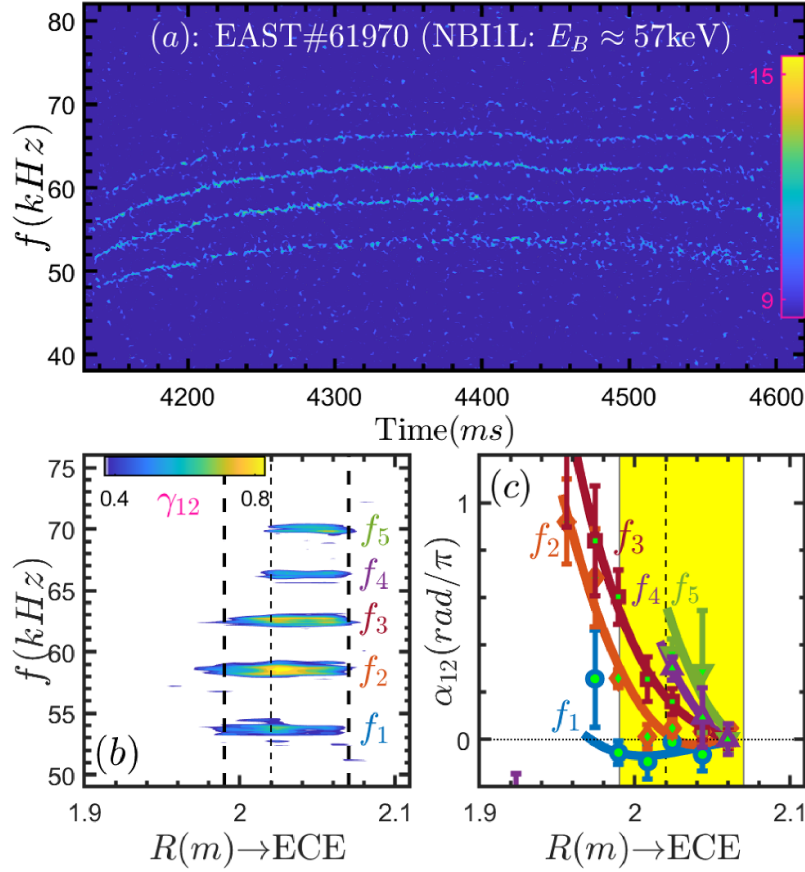


Figure 2. The basic features of BAEs instability measured by the ECE diagnostic. Panel (a) presents the ECE signal spectrogram during the NBII L injection phase, and the corresponding radial coverage of the BAEs branches and their phase angles of mode structure are depicted in panels (b) and (c) respectively.

#61 970. The poloidal structure analysis reveals that the mode exhibits an even symmetry structure of $m = 2$ (or higher order $m = 4$) for the f_1 branch. The poloidal structures vary for the other higher frequency branches, suggesting an increase in m . Furthermore, the toroidal mode number of $n = 1, 2$ are occasionally captured by edge magnetic pickup array for the lower BAE frequency branches in similar discharge condition. Therefore, the toroidal mode numbers for these branches are estimated to be in the range of $1 \leq n \leq 5$.

The plasma confinement is improved for the excitation of BAE instability, as discussed in figure 3. Two time points from shot #61 970 are selected for analysis: $t = 4.4$ s (with BAEs) and $t = 5.4$ s (without BAEs). It can be seen clearly that the toroidal rotation velocity and electron temperature in the core region increase obviously for the excitation of BAEs instability ($\Delta v_{\phi 0}/v_{\phi 0} \approx 20\%$, $\Delta T_{10^0}/T_{10^0} \approx 18\%$). The neutron yield (or fast-ion density) and the ion temperature profile are nearly the same between the two cases. The radial electric field E_r is determined from the ion radial force balance equation [40]: $E_r = \nabla p_i / (Ze n_i) - v_\theta B_\phi + v_\phi B_\theta$, where the p_i is the ion pressure, v_θ and v_ϕ are the poloidal and toroidal velocities and B_θ and B_ϕ the poloidal and toroidal magnetic fields respectively (safety factor $q = r B_\phi / R B_\theta$), Z is the ion charge number and e the elementary charge. The contribution effect of poloidal flow (v_θ) can be predicted by

neoclassical theory, and in some cases it can be omitted due to its smaller value. The two items of radial ion pressure gradient (∇p_i) and toroidal flow (v_ϕ) are estimated from the experimental measurement, as given in the left panel of figure 3. Two time points from shot #61 970 are selected for analysis: $t = 4.4$ s (with BAEs) and $t = 5.4$ s (without BAEs). The neutron yield (or fast-ion density) is nearly the same between the two cases, while the toroidal rotation velocity (v_ϕ) and electron temperature (T_e) in the central region increase dramatically for the case with BAE instability. Consequently, the amplitude of radial electric field (E_r) increases at $R \approx 1.96$ m with the excitation of BAE instability. The $E \times B$ shearing rate $\omega_{E \times B}$ exhibits obvious difference between the BAE-governed inner region ($R \leq 2.02$ m) and BAE-stable outer region ($R \geq 2.02$ m), as marked by the yellow shaded region in the right panel of figure 3, where the $\omega_{E \times B}$ is expressed as [41]: $\omega_{E \times B} \approx r/q \left| \frac{\partial}{\partial r} \left(\frac{q}{r} \frac{E_r}{B_\phi} \right) \right|$. In the region where $R \leq 2.02$ m, the $\omega_{E \times B}$ increases due to the excitation of BAEs, whereas it decreases in the region where $R \geq 2.02$ m, namely the $\omega_{E \times B}$ shear increases dramatically for the existence of BAEs. Therefore, it is reasonable to speculate that when the BAE instability is excited, the radial electric field and shear flow significantly alter the local transport levels, resulting in a substantial increase in the core electron temperature and poloidal rotation velocity.

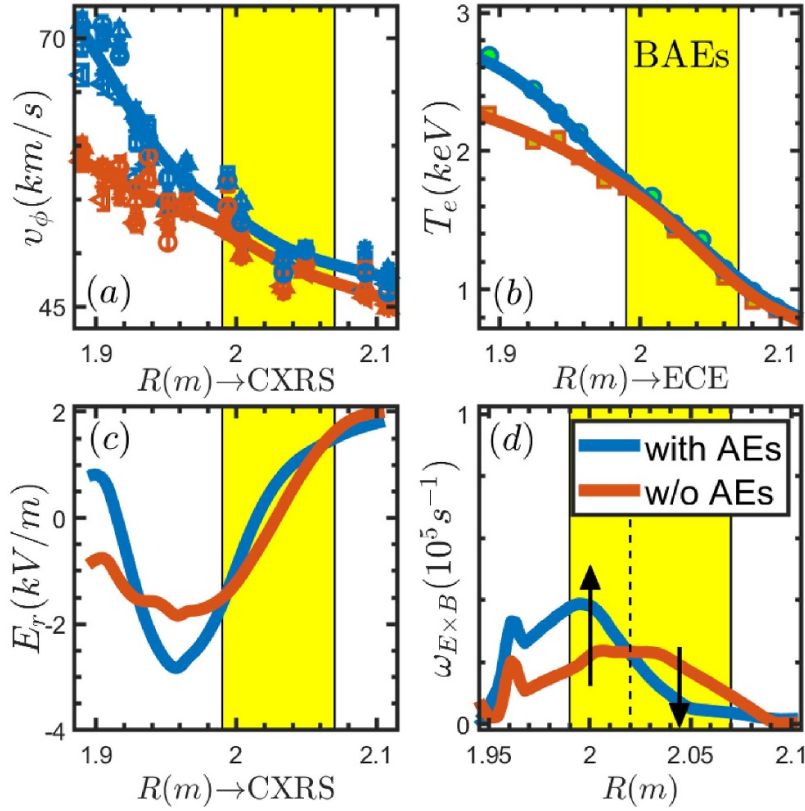


Figure 3. (a) Toroidal rotation velocities, (b) electron temperature, (c) radial Electric fields and (d) $E \times B$ shearing rates for two cases with/without BAE instability in shot #61 970, where the dominant two effects of ∇p_i and v_ϕ are considered.

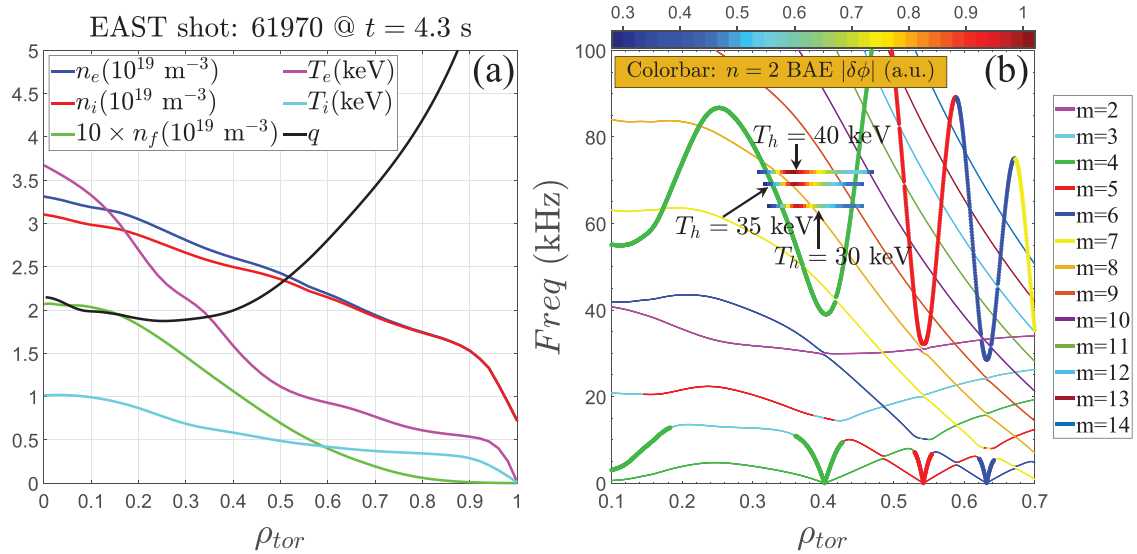


Figure 4. (a) Equilibrium geometry and plasma profiles for #61 970 shot at $t = 4300$ ms. (b) $n = 2$ Alfvén (thick lines) and acoustic (thin lines) continua solved by MAS [46]. The colorbar represents the normalized BAE radial amplitude $|\delta\phi|$.

3. Linear properties

The GTC gyrokinetic simulation model is applied for studying linear and nonlinear dynamics of BAEs [42–44]. To accurately reproduce the conditions of the EAST discharge, realistic experimental geometry and plasma parameters are adopted in the simulations, with the safety factor q and plasma density and

temperature profiles as shown in figure 4(a). Deuteriums are used for both thermal ions and EPs. For the NBI-generated EP population in simulation, the variation of EP temperature profile is usually ignorable and the constant T_h profile is applied in this work, and a local Maxwellian distribution is employed in velocity space. The previous GTC simulations have shown that the unstable TAE excited by a slowing-down distribution

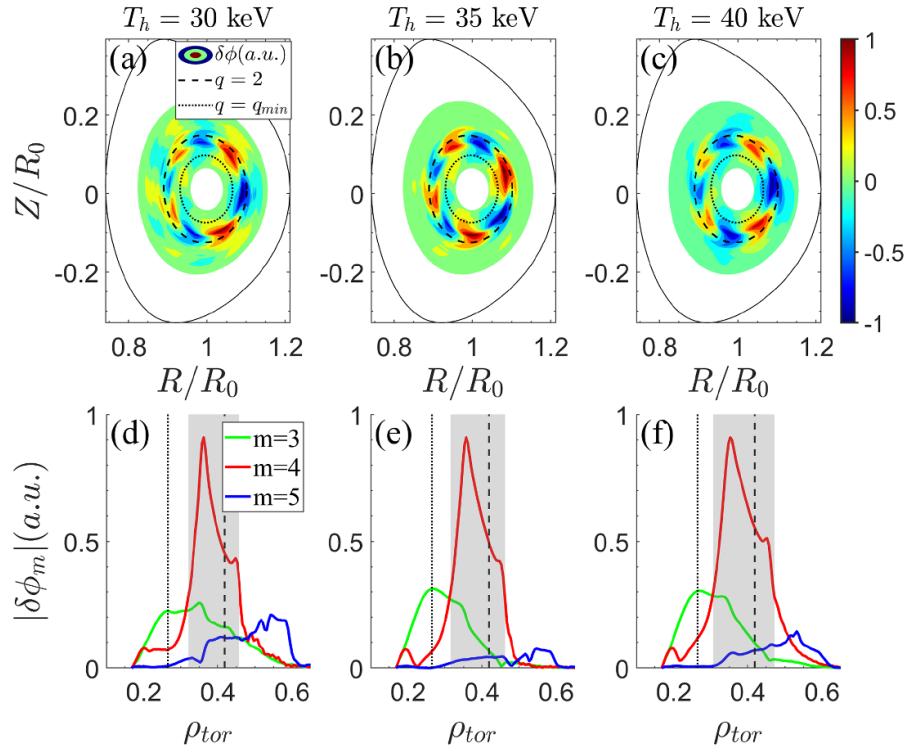


Figure 5. Poloidal mode structure (upper panel) and corresponding m -harmonic radial profiles (lower panel) of $n = 2$ BAE with different EP temperatures. Dashed lines represent the $q = 2$ rational surface, and dotted lines represent the location where $q = q_{\min}$. Gray shaded regions highlight the dominant BAE fluctuation that exceeds 30% of the maximum amplitude.

differs from the Maxwellian case only in small quantitative changes in growth rate and eigenfrequency, while the overall properties remain similar [45]. Therefore, for our purpose of BAE mode identification and basic physical mechanisms, the Maxwellian distribution is sufficient. The T_h varies from 30 keV to 40 keV in different simulation cases, which could cover potential resonance channels for the NBI beam with birth energy of $E_B = 57$ keV in experiments. The on-axis magnetic field strength is $B_0 = 2.2$ T. The toroidal mode number filter in GTC is used in BAE stability study, which enables the wave-particle resonance drive of electromagnetic fluctuations for each n branch. In GTC simulations using the given EAST equilibrium parameters, only $n = 2$ and $n = 3$ BAEs can be driven unstable, consistent with the most unstable BAE branches from ECE measurement as shown in figure 2(a). The radial simulation domain is chosen as $\rho_{\text{tor}} = [0.17, 0.66]$, where $\rho_{\text{tor}} = \sqrt{\psi_t}$ is the normalized radial coordinate. $100 \times 500 \times 30$ grids are used in the radial, poloidal and parallel directions, respectively. Numerical convergence of the simulation results has been verified.

The MAS eigenvalue code [46] is used to calculate the $n = 2$ ideal MHD continua, as shown in figure 4(b). In the core region with reversed magnetic shear ($\rho_{\text{tor}} \sim [0.1, 0.4]$), the continuum accumulation points of both BAE and RSAE exist on $m = 4$ Alfvén continuum as shown by the green curve in figure 4(b), which locate around $\rho_{\text{tor}} \sim 0.4$ with $q = q_{\min}$ and $\rho_{\text{tor}} \sim 0.25$ with $q = 2$, respectively. The core BAE fluctuations observed in experiments range from $\rho_{\text{tor}} = 0.2$ to $\rho_{\text{tor}} = 0.4$ in this region.

3.1. Mode structure, polarization and phase space resonance

Linear simulations are performed to investigate the basic properties of the instabilities under EAST experimental parameters. Figure 5 shows the 2D poloidal and 1D radial profiles of electrostatic potential $\delta\phi$ for the $n = 2$ BAE branch with different EP temperatures. The mode fluctuations peak around the $q = 2$ rational surface rather than the $q = q_{\min}$ surface, confirming the BAE is more unstable than RSAE in consistency with experiments. It is seen that the BAE mode structure exhibits significant up-down poloidal symmetry breaking, deviating largely from the symmetric MHD results. The ‘boomerang’ asymmetric mode structures of BAE have been extensively studied by theory and simulation [47–50], which arises from the anti-Hermitian part of the dielectric tensor corresponding to the non-ideal MHD effects of bulk plasmas and EPs, such as kinetic damping of bulk plasmas and non-perturbative resonance drive of EPs. It is worthwhile mentioning that, as the EP temperature increases in figure 5, both the real frequency and radial width of the BAE increase due to the EP non-perturbative influences, which are also constrained by the Alfvén continuum structure as shown in figure 4(b), namely, BAE eigenstates match the BAE potential well above the bottom of BAE-CAP frequency. For example, the horizontal colorbars represent the radial amplitude profiles of the $n = 2$ BAE with different EP temperatures, demonstrating that the radial width of BAE fluctuations adapts well to the potential well width at corresponding mode frequency.

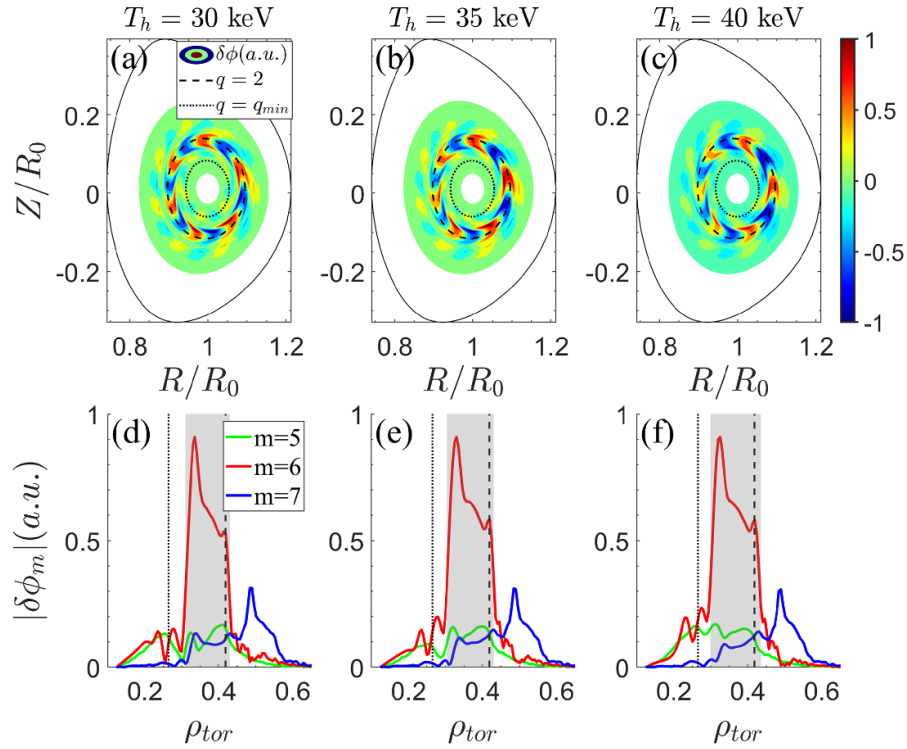


Figure 6. Poloidal mode structure (upper panel) and corresponding m -harmonic radial profiles (lower panel) of $n = 3$ BAE with different EP temperatures. Other details are the same with figure 5.

Figure 6 shows the mode structures for the $n = 3$ BAE under the same EP temperature scan. Compared to the $n = 2$ case, the $n = 3$ BAE exhibits a more radially localized mode structure, which amplifies the EP finite orbit width (FOW) effects that weaken the electromagnetic fluctuations on the EP perturbed distribution evolution, and in turn, decrease the EP non-perturbative influence on BAE mode structure [51], where the $n = 3$ BAE radial width with $T_h = 40$ keV in figure 6(f) is almost identical to $T_h = 30$ keV case in figure 6(d). As n increases, the BAE mode structure becomes narrower and less sensitive to EP drive while the BAE real frequency rises due to the combined effects of stronger EP diamagnetic drift drive, enhanced FOW shielding effect, and increased bulk plasma diamagnetic drift frequency. Linear simulations confirm that both $n = 2$ and $n = 3$ BAEs are more unstable than other n branches, in good agreement with the experimental ECE signal spectrogram in figure 2(b), where the f_2 and f_3 signals dominate.

The radial profiles of parallel electric field $\delta E_{\parallel}$ m -harmonics for $n = 2$ BAE are shown in figure 7. The electrostatic component is defined as $\delta E_{\parallel}^{\text{ES}} = -\mathbf{b}_0 \cdot \nabla \delta \phi$ and the net parallel electric field is $\delta E_{\parallel}^{\text{Net}} = -\mathbf{b}_0 \cdot \nabla \delta \phi - (1/c) \partial_t \delta A_{\parallel}$. It is seen that both the principal dominant poloidal harmonic and sidebands satisfy $|\delta E_{\parallel}^{\text{Net}}| \ll |\delta E_{\parallel}^{\text{ES}}|$, demonstrating the electromagnetic or Alfvénic polarization, where the MHD constraint induces most cancellation between electrostatic and inductive parts. For the dominant poloidal harmonic $m = 4$, the $\delta E_{\parallel}^{\text{ES}}$ profile is barely affected by varying the EP temperature, whereas for the $m = 5$ and $m = 7$ sidebands, $\delta E_{\parallel}^{\text{ES}}$ profile varies significantly between different EP temperature

cases. This is due to the fact that the perpendicular wave-particle energy exchange of $\mathbf{v}_d \cdot \mathbf{E}_{\perp}$ governs the AE and EP interactions [6].

Compared to former studies focusing on the AE mode structure symmetry breaking induced by EP non-perturbative drive [47, 52], our results emphasize that various bulk plasma kinetic effects can also serve as the origin of symmetry breaking, including the diamagnetic drifts, tunneling interaction and mode conversion associated with kinetic Alfvén wave (KAW), Landau resonances, etc.

To provide a complete overview of the linear simulation results across the experimentally relevant n range, we summarize in table 1 the linear stability and real frequencies for all $1 \leq n \leq 5$ branches with different EP temperatures. It should be noted that only two dominant $n = 2$ and $n = 3$ BAEs in figure 2(b) can be driven unstable by EPs in our simulation, while the sub-dominant $n = 1$, $n = 4$ and $n = 5$ branches are stable, which might be due to the difference of EP distribution and plasma equilibrium between simulation and actual experimental condition. The physics mechanism of BAE phase angle variation, i.e. the leading role of bulk plasma kinetic effects rather than EP non-perturbative drive, can be applied to all n branches.

Figure 8 shows the phase space perturbed distribution intensity of EP species δf_h^2 corresponding to $n = 2$ BAE in figure 5. The location and structure of EP resonance islands indicate the specific wave-particle resonance channel and strength. As the EP equilibrium temperature increases, the EP population increases in the high energy regime while decreases in the low energy regime. Therefore, the strength of resonance

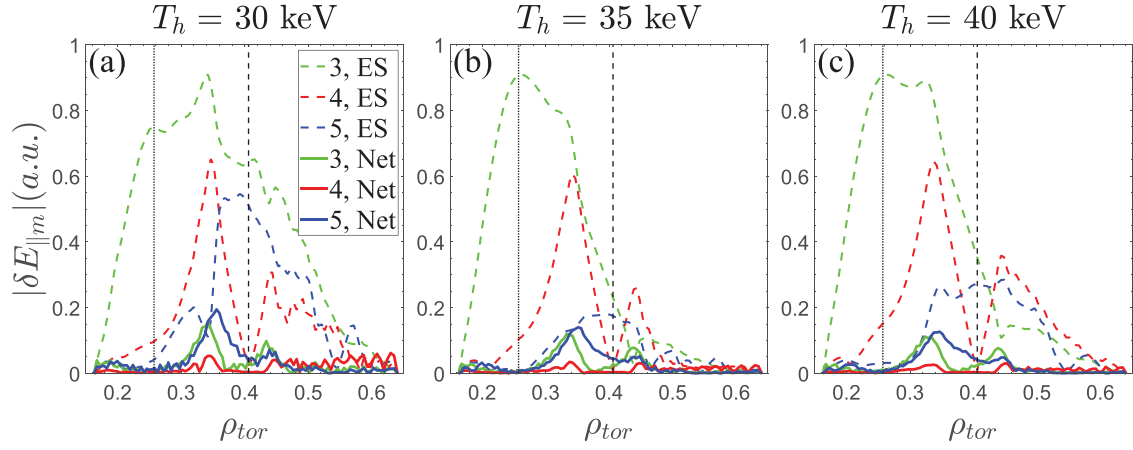


Figure 7. The radial profiles of parallel electric field $\delta E_{||}$ m -harmonic for $n = 2$ BAE. Dashed lines represent the electrostatic component $\delta E_{||}^{\text{ES}} = -\mathbf{b}_0 \cdot \nabla \delta \phi$, and solid lines represent the net parallel electric field $\delta E_{||}^{\text{Net}} = -\mathbf{b}_0 \cdot \nabla \delta \phi - (1/c) \partial_t \delta A_{||}$.

Table 1. Summary of linear GTC simulation results for toroidal mode numbers $1 \leq n \leq 5$ with different EP temperatures.

n	Simulation results	$T_h = 30 \text{ keV}$		$T_h = 35 \text{ keV}$		$T_h = 40 \text{ keV}$	
		$f(\text{kHz})$	γ_L/ω_r	$f(\text{kHz})$	γ_L/ω_r	$f(\text{kHz})$	γ_L/ω_r
1/4/5	No instability observed in GTC	—	—	—	—	—	—
2	BAE from GTC	64.14	0.029	69.07	0.056	71.83	0.078
3	BAE from GTC	67.34	0.004	71.88	0.014	76.77	0.021

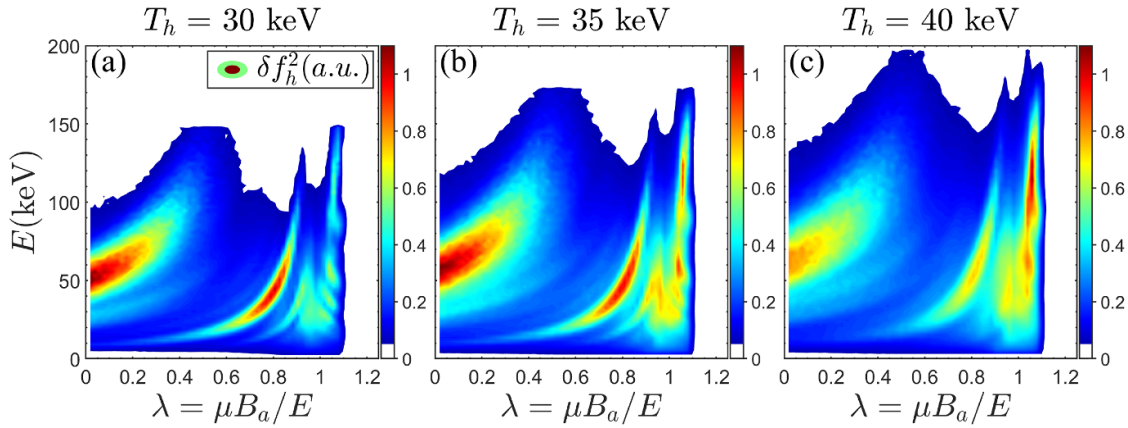


Figure 8. Comparison of phase space EP perturbed distribution intensity δf_h^2 due to $n = 2$ BAE between different T_h values, where the energy E and pitch angle $\lambda = \mu B_a/E$ are the phase space coordinates.

island due to transit motion resonance by passing particle $\omega = \omega_r$, becomes weaker in figure 8(c) than figure 8(a). For comparison, the strength of resonance island due to precessional drift resonance by trapped particle $\omega = n\omega_d$, becomes stronger in figure 8(c) than figure 8(a). This transition is due to the relatively large change on the characteristic frequencies of major EP population by varying its equilibrium temperature while the BAE mode frequency is almost fixed.

3.2. Radial phase variation

The up-down poloidal symmetry breaking of BAE mode structure corresponds to the radial variation of phase angle, which is

defined as $\theta_{rm} = \arctan(\text{Im}(\delta\phi_m)/\text{Re}(\delta\phi_m))$ [50, 53]. Figure 9 compares the phase angle shifts of BAE dominant m -harmonic between $n = 2$ and $n = 3$ branches with different T_h values, i.e. $\Delta\theta_{\text{shift}}(\rho_{\text{tor}}) = \theta_r(\rho_{\text{tor}}) - \theta_r(\rho_0)$, where $\rho_0 = 0.41$ is selected as the reference point in consistency with the ECE diagnostic. As ρ_{tor} increases, the phase angle shift $|\Delta\theta_{\text{shift}}|$ initially decreases and then increases, exhibiting the similar trend with experimental observations on f_1 and f_2 signals in figure 2(c). It is seen that the phase angle variation is more sensitive to the toroidal mode number, where $n = 2$ and $n = 3$ BAEs are characterized by phase angle profiles with large difference, in consistency with figure 2(c) on different radial dependence of phase angle by varying n number. In contrast, the phase angle is barely

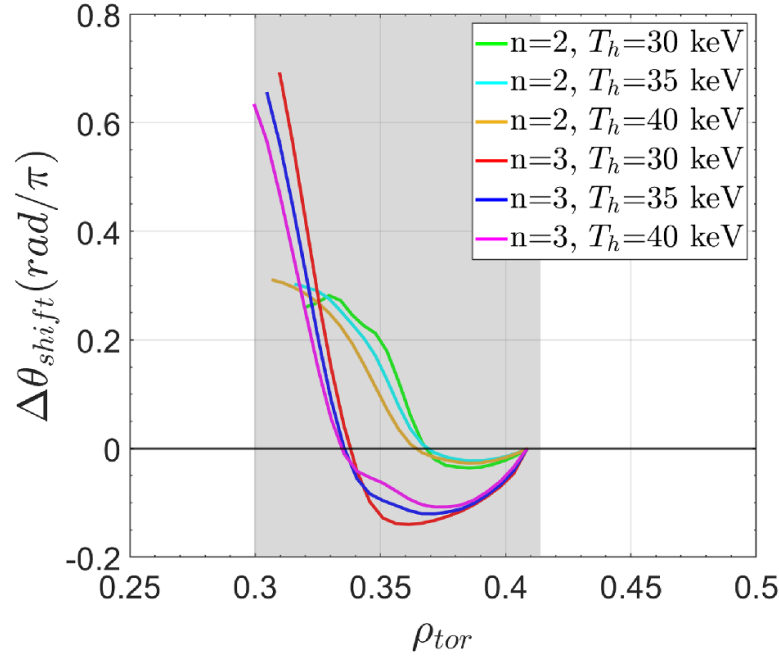


Figure 9. The radial profiles of BAE dominant m -harmonic phase angle $\Delta\theta_{\text{shift}} = \theta_r(\rho_{\text{tor}}) - \theta_r(\rho_0)$ with different T_h values and n numbers, where the reference location $\rho_0 = 0.41$ corresponds to $R \approx 2.06$ m and $\alpha_{12} = 0$ in figure 2(c).

modified by varying EP temperature, implying that the phase angle radial variation and corresponding symmetry breaking is primarily attributed to bulk plasma kinetic effects rather than the non-perturbative EP drive.

Considering the phase space resonance character, the setting of $T_h = 30$ keV is close to experimental condition with tangential NBI injection, and the $n = 2$ BAE dominates over ECE signals in figure 2(b), which is then selected for next nonlinear BAE physics study in section 4.

4. Nonlinear physical processes

In this section, the nonlinear evolution of $n = 2$ BAE with $T_h = 30$ keV is investigated with the ratio of growth rate and real frequency $\gamma_L/\omega_0 = 0.029$. In order to identify the leading saturation mechanism for core BAEs in EAST experiments, we conduct nonlinear simulations without and with considering self-organized zonal fields, which aim to illustrate the roles of nonlinear wave-particle trapping and zonal flow regulation respectively.

4.1. Single- n BAE nonlinear evolution

For single- n BAE nonlinear simulation, the self-organized zonal fields, i.e. the flux-surface averaged components of electrostatic potential $\delta\phi_z$ and parallel vector potential $\delta A_{\parallel z}$ are artificially removed, and wave-particle interaction play the dominant role during nonlinear evolution. Figure 10 presents the nonlinear evolution of the BAE. Figure 10(a) shows the time histories of the principal dominant BAE m -harmonic $\delta\phi_{m=4}$. Figure 10(b) displays the evolution of the mode amplitude $|\delta\phi_{m=4}|$ (red curve) and the dominant frequency ω (black

curve), where the frequency is obtained via wavelet transform of the real part $\text{Re}(\delta\phi_{m=4})$. The corresponding wavelet power spectrum is shown in figure 10(c).

Three representative time steps, t_1 , t_2 and t_3 , are chosen for mode structure and phase space structure analyses, corresponding to the linear stage, initial saturation stage, and nonlinear dissipation stage, respectively. During the linear stage (t_1), the mode grows exponentially with constant frequency, consistent with linear simulation results. As the mode approaches initial saturation (t_2), a rapid frequency downshift is observed: the frequency decreases by approximately 30% within 0.1 ms, indicating a fast chirping process clearly visible in the wavelet spectrum (figure 10(c)). This indicates that the chirping arises from wave-particle interactions rather than from changes in plasma equilibria, consistent with the timescale of fast chirping BAEs observed in previous GTC simulations [26, 27, 31]. In the late dissipation stage (t_3), the mode amplitude gradually decays without frequency restore, which is probably due to the relaxation of EP density profile.

Figure 11 presents the poloidal contour plots of the electrostatic potential $e\delta\phi/T_e$ and the corresponding EP perturbed distribution intensity δf_h^2 in (E, λ) phase space, where E denotes the particle energy and $\lambda = \mu B_a/E$ denotes the pitch angle. During the linear stage (t_1), the mode exhibits a radially broad mode structure peaked around the $q = 2$ rational surface, with the primary wave-particle resonance channel of transit motion resonance due to passing EPs, in consistency with the linear result of figure 8(a). At $t = t_2$ of the initial saturation, the BAE radial width becomes narrower following the downshift of mode frequency. The BAE radial width change with frequency is constrained by continuum structure in figure 4(b), as the frequency nonlinearly decreases, the radial width of BAE potential well becomes

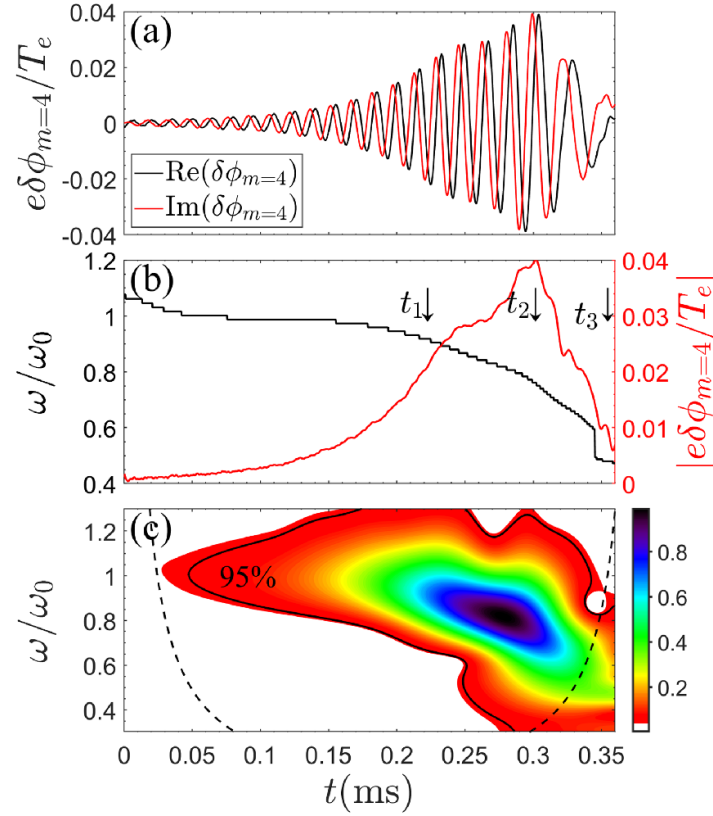


Figure 10. (a) Time history of BAE electrostatic potential $\delta\phi_{m=4}$ in the single- n BAE case without zonal fields. (b) The time evolutions of BAE amplitude $|\delta\phi_{m=4}|$ (red) and dominant frequency ω (black). Three time steps (t_1, t_2, t_3) are chosen for the mode structure and phase space structure analyses, corresponding to different stages of BAE evolution. (c) Corresponding frequency power spectrum.

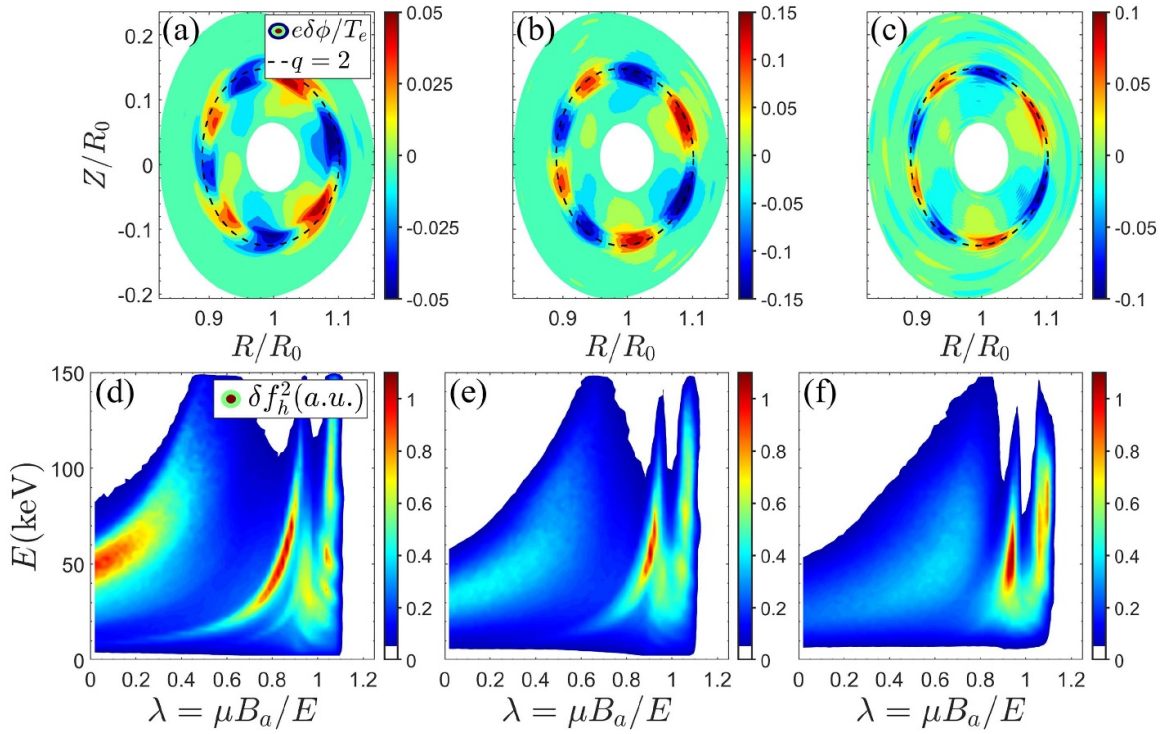


Figure 11. Poloidal contour plots of electrostatic potential $e\delta\phi/T_e$ for $n=2$ BAE at (a) $t=t_1$, (b) $t=t_2$, (c) $t=t_3$ step respectively. (d)–(f) Corresponding (E, λ) phase space structures of EP perturbed distribution intensity δf_h^2 .

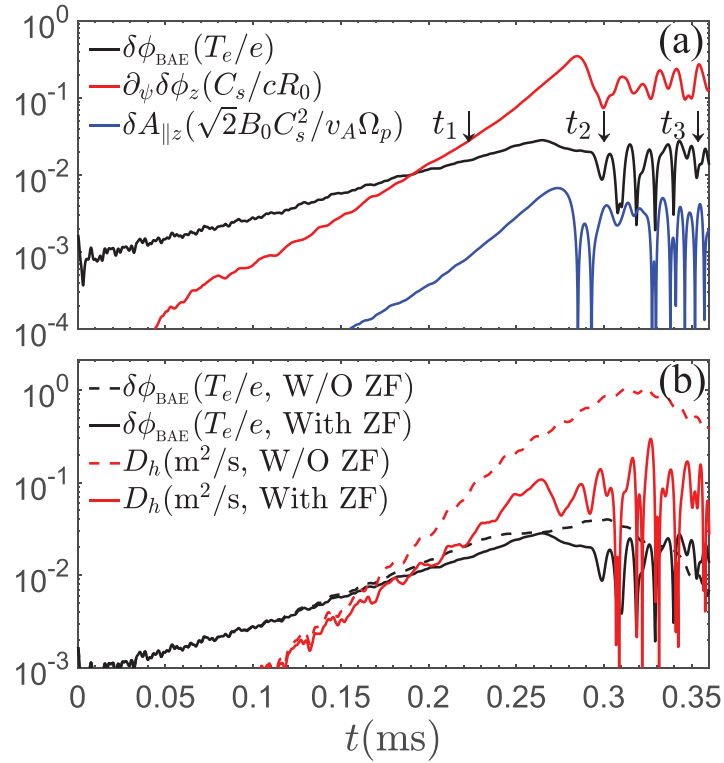


Figure 12. (a) The time evolutions of BAE electrostatic potential $\delta\phi_{\text{BAE}}$, zonal flow $\partial_\psi \delta\phi_z$, and zonal current $\delta A_{\parallel z}$. The zonal fields are beat-driven with a twice BAE linear growth rate, i.e. $\gamma_{\text{ZF}} = 2\gamma_{\text{BAE}}$. (b) Comparisons of $\delta\phi_{\text{BAE}}$ and EP particle diffusivity D_h between cases without and with zonal fields.

narrower and enhances the bulk plasma damping on BAE fluctuations extending into continuum. Meanwhile, the transit motion resonance island moves to the lower energy regime, the bounce and precessional drift resonance island becomes smaller in figure 11(e), because the downshift of BAE frequency modifies the resonance conditions. This phenomenon can be explained by fishbone paradigm on the non-adiabatic chirping process [54]. The nonlinear wave-particle interaction between BAE and EPs significantly change the mode dispersiveness, namely, the BAE real frequency, mode structure and phase space structure in our simulation. The BAE stability is most determined by EP drive and bulk plasma damping. In the nonlinear stage, the first one can be weakened by the phase space hole-clump structure, and the second one can be enhanced due to the frequency downshift, which eventually balance with each other giving rise to the nonlinear saturation. In the dissipation stage (t_3), the radial width of BAE mode structure further decreases without restore in figure 11(c), and corresponding phase space resonance islands move to the lower energy regime, indicating the continuous downshift of BAE frequency due to the EP density profile relaxation. As the bulk plasma damping exceeds the EP drive, the BAE fluctuations with fine radial structure eventually dissipate.

However, above fast frequency chirping is not observed in the ECE signals from figure 2(a), which does not exhibit significant frequency change on sub-millisecond timescale, and only the sweeping phenomena on much longer timescale of 10–100 ms. Therefore, it suggests that the single- n BAE picture, which excludes zonal

field dynamics, is insufficient to explain the experimental observations.

4.2. Effect of beat-driven zonal flow on BAE saturation

In this subsection, the nonlinear evolution of BAE is investigated with keeping self-organized zonal fields, which further incorporates the zonal field influences on BAE saturation and frequency spectrum.

The time evolutions of BAE principal dominant m -harmonic $\delta\phi_{\text{BAE}}$, zonal flow $\partial_\psi \delta\phi_z$, zonal current $\delta A_{\parallel z}$ are shown in figure 12(a). It is seen that during the linear stage of $t < 0.25$ ms, the zonal fields are excited with a twice BAE linear growth rate, i.e. $\gamma_{\text{ZF}} = 2\gamma_{\text{BAE}}$, suggesting the beat-driven process due to nonlinear coupling between pump BAE and its complex conjugate. In figure 12(b), we compare the $\delta\phi_{\text{BAE}}$ and EP particle diffusivity with and without keeping zonal fields. It should be mentioned that zonal flow dominates over zonal fields and plays the leading role on the interaction with pump BAE, and the zonal current influence is ignorable. The zonal flow can effectively lower the BAE saturation amplitude and reduce the EP transport coefficient. With zonal fields, the BAE saturation amplitude decrease from $e\delta\phi/T_e \approx 0.040$ to $e\delta\phi/T_e \approx 0.028$ in figure 12(b), which is below the threshold for nonlinear frequency chirping onset as shown in figure 10(b). Therefore, the nonlinear frequency chirping of BAE does not happen in presence of self-organized zonal flow. The zonal flow reduction on core BAE fluctuations and EP transports, can be intuitive and consistent with the observation

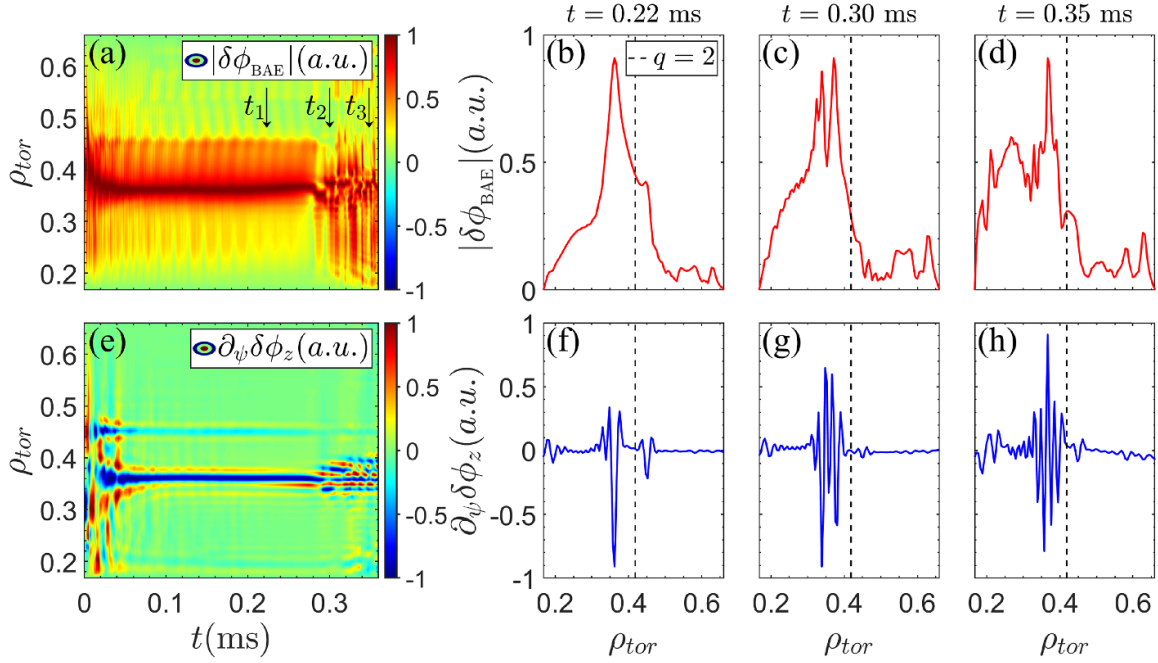


Figure 13. (a) and (e) The radial-time plots of surface-averaged BAE fluctuation intensity $|\delta\phi_{\text{BAE}}|$ and zonal flow $\partial_\psi \delta\phi_z$ respectively, which are renormalized in the same range for each time step. (b)–(d) The radial profiles of $|\delta\phi_{\text{BAE}}|$ at $t = t_1$, $t = t_2$ and $t = t_3$ time steps. (e)–(h) The radial profiles of $\partial_\psi \delta\phi_z$ at $t = t_1$, $t = t_2$ and $t = t_3$ time steps.

from other gyrokinetic and kinetic-MHD hybrid simulations [28, 32, 55–57].

The time evolutions of BAE fluctuation intensity $|\delta\phi_{\text{BAE}}|$ and zonal flow $\partial_\psi \delta\phi_z$ are shown in figures 13(a) and (e) respectively, where the amplitudes are renormalized by maximal values at each time step so that the radial structure can be clearly reflected during all stages. It is seen that during the linear stage $t < 0.25$ ms, the radial structures of both the pump BAE and zonal flow remain steady state as shown in figures 13(b) and (f) respectively. Specifically, the fine radial-scale structures of zonal flow in figure 13(f), peak at the radial locations where $n = 2$ BAE with $T_h = 30$ keV intersects with Alfvén continuum as shown in figure 4(b), namely, $\rho_{\text{tor}} \approx 0.35$ and $\rho_{\text{tor}} \approx 0.45$. The BAE-continuum interaction induces the mode conversion to KAW and strong radiative damping, resulting in the sharp change of BAE radial structure at $\rho_{\text{tor}} \approx 0.35$ and $\rho_{\text{tor}} \approx 0.45$ as shown in figure 13(b), and then enhance the radial derivative for zonal flow generation. At the initial saturation stage of $t_2 = 0.30$ ms, the fine scale components increase for both pump BAE and zonal flow as shown in figures 13(c) and (g) respectively, suggesting the zonal flow scattering of pump BAE. At the dissipation stage of $t_3 = 0.35$ ms, the fine scale components dominate over pump BAE and zonal flow, as shown in figures 13(d) and (h) respectively, which are eventually damped by bulk plasma damping.

In order to quantitatively understand the zonal flow scattering effect on pump BAE, we calculate the zonal flow shearing rate for each time step, i.e. $\omega_{E \times B} = r/q \left| \frac{\partial}{\partial r} \left(\frac{q}{r} \frac{E_r}{B_\phi} \right) \right|$, as shown in figure 14, where E_{r_z} is the radial electric field generated by zonal flow. It is seen that the BAE remains linear growth when the shearing rate exceeds the growth rate $\omega_{E \times B} > \gamma_L$ (note

that $\gamma_L \approx 0.029\omega_0$), and gets saturated by zonal flow scattering until the shearing rate becomes on the same order with BAE real frequency, i.e. $\omega_{E \times B} \sim \omega_0$ around $t = 0.28$ ms. Therefore, our simulation supports the view that for dissipative instability such as BAE with $\gamma_L/\omega_r \ll 1$, the criterion of zonal flow regulation becomes $\omega_{E \times B} > \omega_r$ rather than $\omega_{E \times B} > \gamma_L$ [58]. For comparison, the zonal flow regulation on drift-wave turbulence adopts $\omega_{E \times B} > \gamma_L$ as the threshold [59], because drift-wave instabilities are mostly reactive type with $\gamma_L \sim \omega_r$.

It should be pointed out that the experiment results of radial electric field E_r and shearing rate in figure 3 are calculated based on radial force balance equation, of which time scale is the plasma equilibrium evolution, rather than the simulation results of zonal flow beat-driven by core BAEs. However, the simulation and experiment are consistent with each other on improving plasma confinement from following aspects. (i) The experimental measured $\omega_{E \times B}$ exhibits a nearly twice increase in the region with core-BAE activity, which is due to the increase of plasma temperature and toroidal rotation velocity as an internal transport barrier (ITB). (ii) The maximal shearing rate of BAE-ZF in figure 14 is $\omega_{E \times B} \sim 6 \times 10^5 \text{ rad s}^{-1}$, which can be much larger than the growth rates of most drift-wave instabilities with $\omega_{E \times B} \gg \gamma_{\text{DW}}$, and thus the BAE-ZF are able to suppress turbulent transport and favors the ITB formation.

In a short summary, the self-organized zonal flow beat-driven by core BAEs, can effectively decrease the BAE saturation amplitude, remove the non-adiabatic fast frequency chirping, and potentially suppress the drift-wave turbulence and thus improve the core confinement. The zonal flow regulation (scattering) criterion for dissipative-type instability (such

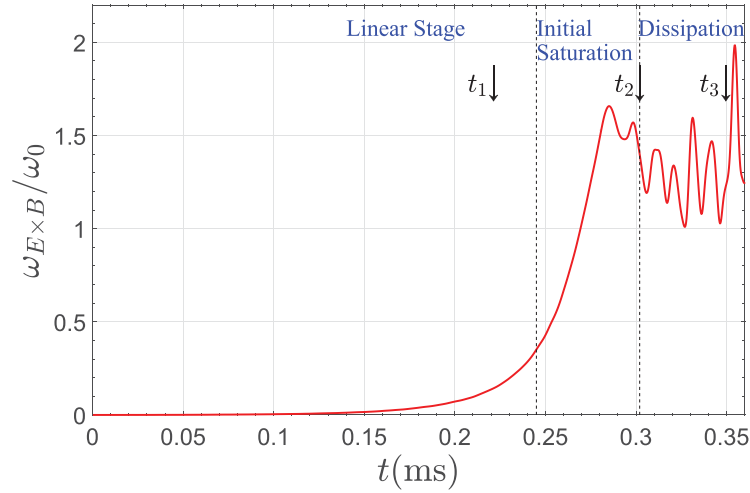


Figure 14. Time evolution of zonal flow shearing rate $\omega_{E \times B}$ normalized by BAE linear frequency ω_0 . t_1 , t_2 and t_3 time steps correspond to three stages of BAE evolution, namely, linear stage, initial saturation and dissipation respectively.

as BAE) becomes $\omega_{E \times B} > \omega_r$, while the traditional $\omega_{E \times B} > \gamma_L$ is only valid for reactive-type instability with $\gamma_L \sim \omega_r$.

5. Summary and discussion

In NBI heating plasmas on the EAST tokamak, low- n electromagnetic modes with zonal flows have been observed and investigated in discharge #61 970. Experimental results indicate that core-localized BAEs with toroidal mode numbers $1 \leq n \leq 5$ are excited by tangentially injected NBI in the central region $0.2 \leq \rho \leq 0.4$, accompanied by an increase in the $\omega_{E \times B}$ shear and improvement of plasma confinement in the core region. The ECE spectrum reveals that these Alfvénic fluctuations have frequencies in the range of $50 \leq f \leq 70$ kHz, and the radial profiles of the phase angle vary significantly with the toroidal mode number n .

Based on experimental equilibrium parameters, GTC simulations are performed to understand the underlying physics of BAE excitation and saturation. Linear simulations identify that $n=2$ and $n=3$ BAEs can be excited, primarily localized around the $q=2$ rational surface, correlated with the experimental spectrogram. The mode structure exhibits a ‘boomerang-shaped’ asymmetric structure, deviating from the ideal MHD symmetric eigenmode. This poloidal symmetry breaking gives rise to radial phase variation, which is found to depend strongly on the toroidal mode number n but negligibly on EP temperature, suggesting that it is primarily attributed to bulk plasma kinetic effects rather than non-perturbative EP contributions. BAE-EP phase space resonance analysis reveals that at $T_h = 30$ keV, a significant resonance island exists in the passing particle region, closely matching the experimental condition with tangential NBI injection.

Nonlinear simulations with $T_h = 30$ keV are performed to elucidate the BAE saturation physics. First, considering only single- n BAE dynamics, it is found that after mode saturation, the frequency rapidly downshifts by approximately 30% within 0.1 ms. This fast chirping, accompanied by a narrowing of the mode structure consistent with the Alfvén continuum

potential well, arises from wave-particle resonant interactions rather than equilibrium parameter variations. However, the rapid frequency chirping is not observed in experiment, and thus the single- n BAE nonlinear evolution is insufficient.

Nonlinear simulations of both BAE and self-organized zonal fields find that zonal flow significantly reduces BAE saturation amplitude and EP diffusion coefficient, eliminating the fast chirping by reducing the BAE amplitude below the chirping threshold. The zonal fields are excited via beat-driven process with a twice linear growth rate of BAE pump wave. As the zonal flow shearing rate exceeds BAE real frequency $\omega_{E \times B} > \omega_r$, the zonal flow regulation (scattering) effect is greatly enhanced and leads to the BAE saturation, which differs from the criterion of zonal flow regulation on drift-wave turbulence $\omega_{E \times B} > \gamma_L$. In general, the zonal flow plays the governing role during the nonlinear BAE evolution in EAST NBI heating plasmas, which suggests a possible mechanism for the improved plasma confinement. Understanding the characteristics of core BAEs in EAST NBI heating plasmas, is helpful for optimizing experiment parameters, and the relevant mechanisms are useful for explaining similar phenomena in different machines.

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