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THE RESEARCH OF THE STABILITY OF REVERSED SHEAR ALFVÉN EIGENMODES EXCITED BY ENERGETIC PARTICLES IN HL-2A
Analysis of the Possible Presence of RSAE-like Modes and RSAEs in HL-2A

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Abstract

To our knowledge, this study represents one of the first systematic gyrokinetic simulations with the Gyrokinetic Toroidal Code (GTC) on the HL-2A tokamak, focusing on suspected reverse-shear Alfvén eigenmodes (RSAE) in discharge #27055 (H-mode, high β, reverse magnetic shear). Given the limited prior work on Alfvén eigenmodes (AE) under HL-2A conditions, we cautiously refer to the observed instability as "RSAE-like," highlighting its chirping behavior while noting structural differences from classical RSAE. Linear multi-n simulations, based directly on experimental profiles, identify the dominant mode as $n = 2$, exhibiting RSAE-like chirping into the TAE band with radial migration. Sensitivity scans using equilibria reconstructed with varied q-profiles reveal that qmin exerts decisive control on mode existence, frequency, and growth rate: as qmin approaches 2, both linear drive and saturation amplitude are significantly reduced. Since the nonlinear behavior of the dominant mode is difficult to characterize, we instead perform nonlinear single-n simulations focusing on the subdominant mode with $n = 4$. It shows rapid zonal flow (ZF) growth with rates about twice the linear mode growth rate, effectively suppressing RSAE-like activity. Energetic particle transport is weak in the linear phase but intensifies markedly after saturation, correlating with chirping and structural evolution toward the TAE regime. Comparison with simulations and experiments from other devices confirms universal features—such as chirping–migration–transport coupling—while also identifying HL-2A-specific dependencies on q-profile, β, and energetic particle distribution. This sequential workflow, in which linear analysis provides experiment-based mode selection and nonlinear studies enable validation against broader theory and multi-device results, establishes a quantitative framework for diagnosing and controlling AE-like instabilities in HL-2A and suggests directions for future experiment–model integration.

1. BACKGROUND AND MOTIVATION

In the pursuit of advanced or hybrid scenarios for future devices such as ITER, reversed or low magnetic shear q-profiles have emerged as essential means to sustain long-lived internal transport barriers with steep pressure gradients. These profiles are often accompanied by strong plasma shaping, including high elongation and

significant triangularity. While such geometric and equilibrium features can suppress certain macroscopic MHD instabilities and improve energy confinement, they also create wide frequency gaps in the Alfvén continuum, in which various Alfvén eigenmodes (AEs)—including TAEs, RSAEs/Alfvén cascades, and BAEs—can be localized and destabilized by super-Alfvénic energetic particles. Once excited, these modes can efficiently enhance radial transport and losses of energetic particles through mechanisms such as resonant absorption and phase-space redistribution, thereby degrading confinement and potentially threatening device integrity. Accordingly, identifying, interpreting, and assessing the controllability of these instabilities is of direct relevance to the feasibility and operational safety margins of ITER advanced scenarios.

Among the spectrum of AEs, reversed shear Alfvén eigenmodes (RSAEs) are particularly critical due to their sensitive coupling to the minimum of the q-profile, q_{min}. The characteristic "cascade" phenomenon observed in experiments—where multiple harmonics are excited as q_{min} crosses successive low-order rational values—not only enriches the dynamics of the modes but has also been widely exploited as a diagnostic tool for q-profile evolution and the location of transport barriers. Furthermore, RSAEs can couple or convert into TAEs, generate higher harmonics, and trigger enhanced energetic particle losses during nonlinear evolution. Such complex behaviours have been observed across a range of devices, from conventional large tokamaks to spherical tori, underscoring the limitations of purely linear or ideal MHD descriptions in capturing their experimental manifestations.

Theoretical and numerical studies demonstrate that accurate characterization of these instabilities and their impact on energetic particle transport requires inclusion of multiple physical effects: toroidal geometry, plasma shaping (elongation, triangularity), finite pressure and pressure gradient, finite Larmor radius (FLR) corrections, and the kinetic responses of both thermal and energetic particles. Thermal ion kinetics are especially important—not only providing damping channels that saturate certain modes but also modifying the continuum and mode structure, thereby influencing mode frequency and growth. Moreover, although kinetic-scale drift waves and turbulence (such as ITG modes) and AE dynamics are separated in frequency and spatial scales, strong cross-scale coupling can still arise. This occurs through processes such as the generation and destruction of zonal flows and zonal structures, or turbulence-induced scattering of energetic particles, which in turn regulate AE nonlinear dynamics and associated energetic particle transport.

The nonlinear saturation mechanisms of AEs and the resulting magnitude of energetic particle transport remain among the key unknowns for predicting fast-particle confinement in burning plasmas. Existing first-principles simulations have primarily focused on AE–energetic particle nonlinear dynamics, while the simultaneous inclusion of microturbulence, kinetic electrons, electromagnetic effects, and realistic global geometry has been long hindered by computational and modeling limitations. Recent advances in global gyrokinetic particle simulations (e.g., GTC[1]) and hybrid MHD–gyrokinetic approaches (e.g., HMGC, XHMGC) have significantly extended these capabilities, enabling the incorporation of kinetic electrons, electromagnetic perturbations, experimental equilibria, and full toroidal geometry. These studies have begun to reveal the nonlinear interplay between AEs and turbulence as well as among different particle populations. Notable findings include AE saturation through self-generated $m = n = 0$ zonal flows and zonal structures, substantial damping by thermal ion kinetics, FLR-induced reduction of drive and growth rates, and turbulence-induced modification of phase-space distributions that ultimately enhance energetic particle transport.

Given this intricate physics and multi-scale coupling, reliable extrapolations to ITER conditions must rest on comprehensive, nonlinear, global simulations in realistic toroidal geometry, incorporating both thermal and energetic particle kinetics together with electromagnetic effects, and validated against experimental observations of mode frequencies, structures, damping, and energetic particle losses. While recent numerical advances have achieved important progress in both simulation fidelity and physical modeling, further extension to longer timescales and higher-fidelity multi-scale computations is essential. Such efforts will be critical to quantify the contributions of instabilities to fast-particle transport, identify dominant saturation pathways, and develop effective mitigation strategies, thereby providing a robust physical basis and engineering support for advanced operational scenarios in ITER and other large-scale fusion devices.

2. SIMULATION SETUP

We selected the EFIT magnetic-equilibrium geometry and plasma profiles of the high-β H-mode HL-2A discharge #27055 at 602 ms, including the distributions of various particle species, as shown in Fig. 1(a). Here, the radial coordinate is defined on the midplane with the magnetic axis as the origin and increasing outward. The safety-factor q profile exhibits reversed shear Fig. 1(b), with a minimum around $q_{min} \approx 1.5$, near which

energetic particles (EPs) can excite RSAE-like modes. Why do we refer to it as RSAE-like, and how does it differ from the canonical RSAE? According to our survey, RSAE excitation generally requires that the minimum of the q profile be close to a rational value, which produces an appropriate gap in the Alfvén continuum at that location and leads to a specific instability. There is no strict criterion for the exact rational value of $q_{\min}$; nevertheless, analyses on devices such as DIII-D and JET uniformly indicate that reversed magnetic shear leads to a particular modification of the Alfvén continuum, with the degree of modification depending intricately on experimental conditions. The significance of the present work is that, although the HL-2A continuum in this shot is nonstandard, it still exhibits certain RSAE characteristics. This fills a gap in previous analyses, extends the scope of the RSAE-like definition, and enables investigation of its properties. To study the sensitivity of the HL-2A Alfvén continuum to $q_{\min}$, we also constructed a new equilibrium with $q_{\min} \approx 2$ by modifying the EFIT inputs and re-solving the Grad–Shafranov equation, enabling a direct comparison between the original and adjusted equilibria.
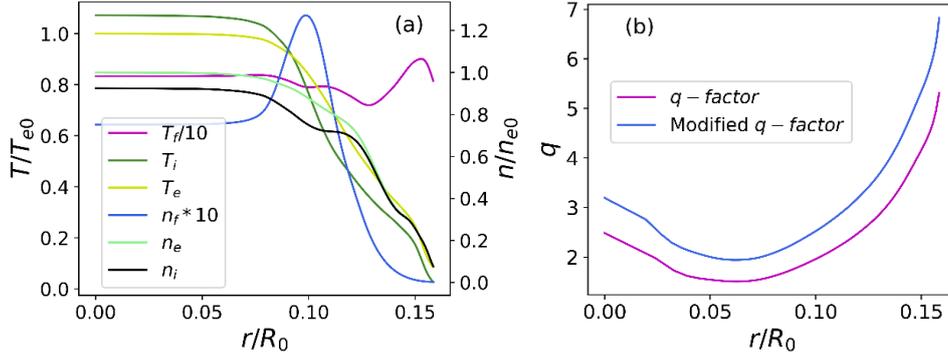

FIG. 1.   *Simulation cross-sectional setup: (a) Temperature and density profiles of all particle species; the fast-ion profiles are scaled. (b) Original q profile and the intentionally adjusted q profile.*

In this study, GTC employs gyrokinetic ions and drift-kinetic electrons. All particle species (EPs, thermal ions, and electrons) are treated using the low-noise δf scheme, and the electron response is further extended with a fluid–kinetic hybrid model. Each species uses a fixed global equilibrium pressure profile. It has been verified that, in global gyrokinetic simulations of microturbulence, using fixed global profiles does not alter the physics of nonlinear RSAEs, nor the role of zonal flows in RSAE saturation and in the nonlinear evolution of RSAE mode amplitude. Guided by related RSAE studies and the high-frequency H-mode discharge characteristics of HL-2A, the time step is set to 10^{-8} s. A global field-aligned grid with 32 parallel planes is used, together with 500×100 unstructured perpendicular mesh elements. For each particle species, 750 locally Maxwellian markers are loaded per cell, ensuring adequate resolution of RSAEs in the tokamak. We also performed verification and validation with higher grid density and smaller time steps to exclude numerical instabilities. In the simulations below, Fourier filtering is applied to select specific toroidal mode numbers while retaining all poloidal harmonics.

3.   LINEAR RESULT

First, in conjunction with HL-2A experimental observations, we found that for toroidal mode numbers $n \geq 2$ multiple modes exhibit upward frequency chirping. Accordingly, we retained modes with $n = 2\text{–}9$ and performed linear simulations for the toroidal harmonics most relevant to the RSAE-like activity. The linear

simulation results indicate that during the linear growth phase the n = 2 mode is dominant while the other modes remain subdominant. Therefore, we proceeded to carry out single-n toroidal simulations focused on n = 2.
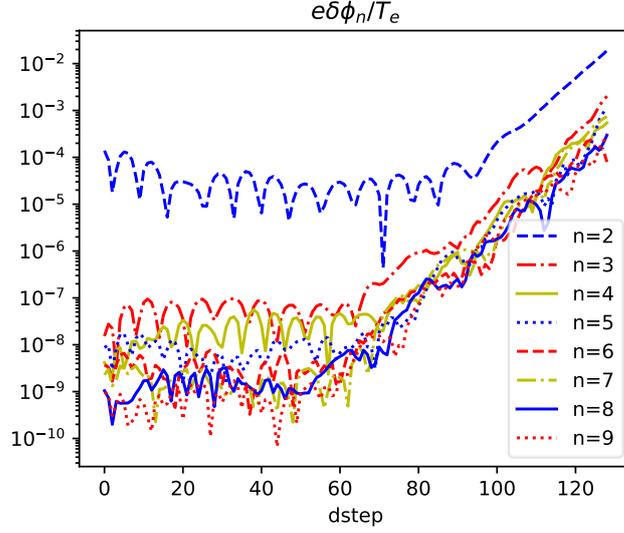

FIG. 2. *Multi-toroidal-mode linear simulation results for HL-2A shot #27055. The figure shows the evolution of the perturbed electrostatic potential of each mode over the simulation time steps.* $n = 2$ *is the dominant mode.*

3.1. Change q profile

By solving the Alfvén continuum of HL-2A, we found that the continuum does not match classical theoretical and experimental results and instead resembles the TAE case, although experiments do show frequency sweeping. By self-consistently adjusting the magnetic-field distribution we obtained modified experimental profiles. Within the approximation range, starting from two reference cases with $q_{min} \approx 2$ and $q_{min} \approx 1.5$, respectively, we scanned the q profile upward in steps of $\Delta q_{min} = 0.1$ [2]. Under these approximations we obtained 11 magnetic configurations with q_{min} ranging from ≈ 1.5 to ≈ 2.5 (i.e. $q_{min} \approx 1.5, 1.6, ..., 2.5$). Keeping all other experimental parameters self-consistently fixed, we solved the Alfvén continuum for $n = 2$. We considered two treatments: the conventional AE slow-sound approximation used at low β, and, to capture physics relevant to HL-2A's relatively high $\beta \approx 0.98$, an exact solution including acoustic coupling of the Alfvén continuum.
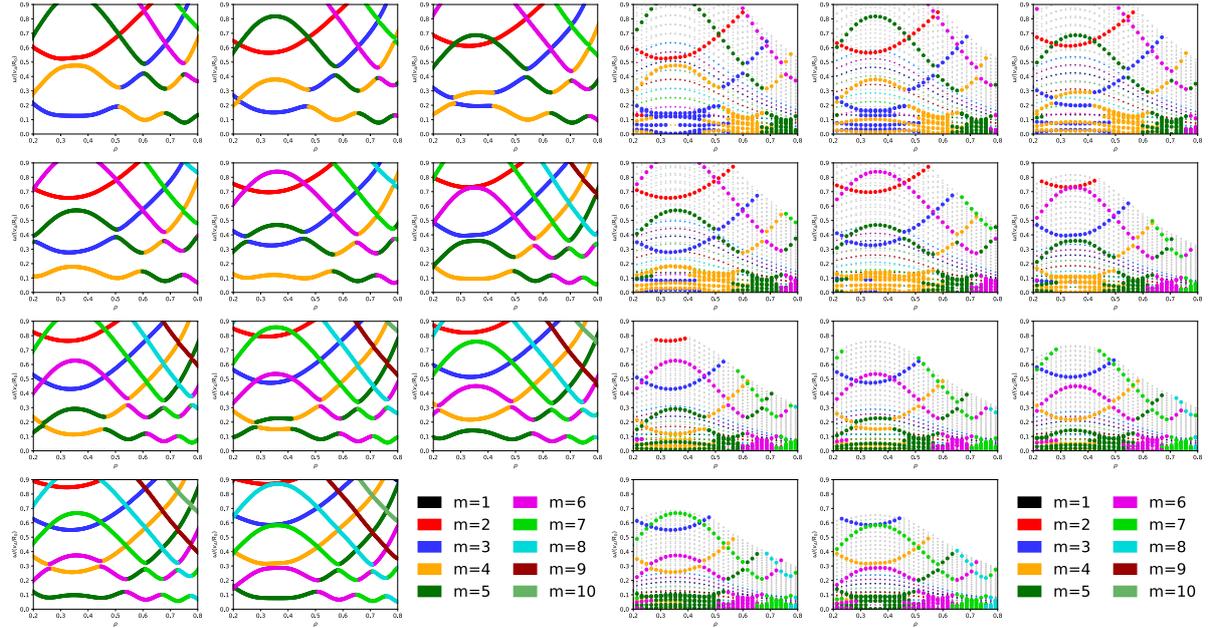

FIG. 3. *The figure shows the Alfvén continua for the 11 configurations computed with two different approximations: the left panels use the slow-sound approximation, while the right panels include the exact acoustic coupling.*

From the figure it is clear that as $q_{\min}$ increases, the low-β solution produces smaller gaps, implying stronger continuum damping; while at high-β the gaps also shrink, the overall extent of the continuum decreases, meaning perturbations outside that reduced range will not be subject to continuum damping. At the same time, we observe that as $q_{\min}$ is raised the low-β continuum structure becomes more similar to the conditions required for a classical RSAE to occur, which motivates us to verify whether the $n = 2$ mode exhibits RSAE-like behavior.

3.2. Frequency upsweeping and growth-rate reduction

Based on these 11 cases, we performed linear simulations for $n = 2$. Coincidentally, the dominant poloidal harmonic in every case is $m = 3$, so we measured the mode frequency and linear growth rate of the mode $(2,3)$ to study its relation with the continuum. In the $q_{\min} = 1.5–1.6$ stage the $(2,3)$ frequency lies in the TAE gap, and in the large gap the growth rate is also large (more unstable). As $q_{\min}$ is raised the continuum develops RSAE-like features: the $(2,3)$ frequency rises rapidly (i.e. energy shifts to the high-frequency branch), the low-frequency part is removed by continuum damping, and the growth rate falls — exactly the signature of an RSAE. With further increase of $q_{\min}$ we observe non-classical mode evolution under high-β conditions: the low-β continuum constraint becomes ineffective, the $(2,3)$ mode then follows the high-β continuum damping behavior and converts into a BAE; as the continuum compresses the growth rate gradually decreases and the mode shifts radially outward, eventually turning into a new TAE.
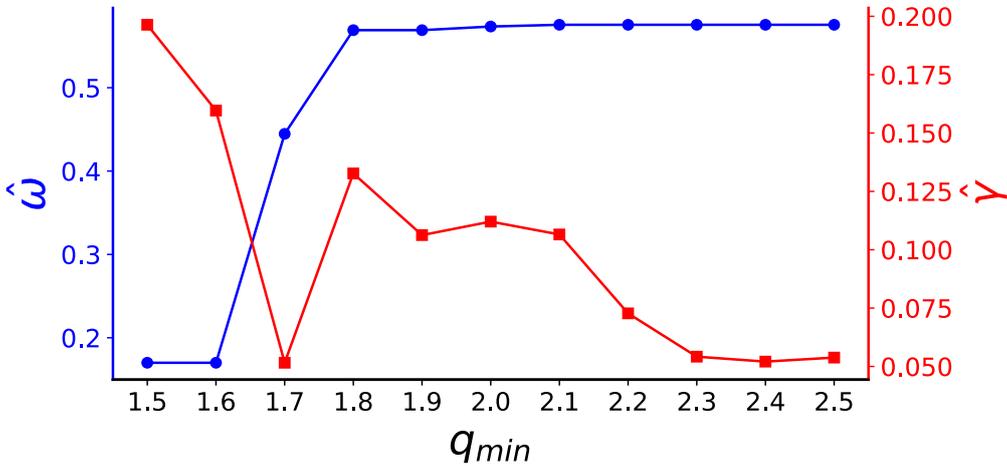

FIG. 4.   *Dependence of the normalized frequency and growth rate of the $(2,3)$ mode on q_{min}.*

4.   NONLINEAR RESULT

It seems that, given the current progress, further nonlinear simulations should be carried out for $n = 2$ to study its nonlinear saturation properties. Unfortunately, due to the high experimental parameters we could not find suitable simulation settings that resolve the nonlinear physics; this is a direction we plan to explore further. By analogy with the detailed theoretical and experimental analyses on DIII-D[3], we performed nonlinear simulations for the subdominant unstable mode $n = 4$ and $n = 6$. The instability observed in HL-2A is not fully consistent with DIII-D RSAE characteristics — as our linear simulations also showed, it is more TAE-like. Under reversed magnetic shear it can be regarded as a distinct kind of instability, which we call a RSAE-like mode. Below we study the effect of zonal flows[6] on the nonlinear saturation of the RSAE-like mode.

4.1. $n = 4$ and $n = 6$.

Fig.6. (n4case1) shows the turbulence self-sustained zonal flows and the evolution of the normalized electrostatic potential $e\delta\phi/T_e$ on the $q_{\min}$ flux surface as a function of time (R_0/C_s). For the most unstable mode $n = 4$, which has a linear growth rate γ with $\gamma/\omega \approx 4\%$ (here ω is the real frequency), the RSAE saturates at a relatively high level. The turbulence-generated zonal flows strongly sustain the RSAE, yielding a nonlinear growth rate of 2γ and absorbing additional energy during the nonlinear phase.

In Fig.5. (a1) and (a2) we diagnose the cross-sectional distributions of the perturbed electrostatic potential in the mode-formation, linear-growth and nonlinear-saturation stages shown in Fig.6. In Fig.5. (a) a RSAE-like mode

near q_{min} is clearly visible. Our identification is based on the continuum[4], which shows that the reversed magnetic shear geometry stretches the Alfvén continuum near q_{min} in both the radial and poloidal directions, thereby creating conditions favourable for instability. Compared with other devices, whose q_{min} values are closer to an integer and therefore produce larger changes in the continuum shape and branch crossings (which favour mode control), the HL-2A result is not a typical RSAE (the canonical RSAE structure appears in our later, artificially adjusted q-profile simulations).
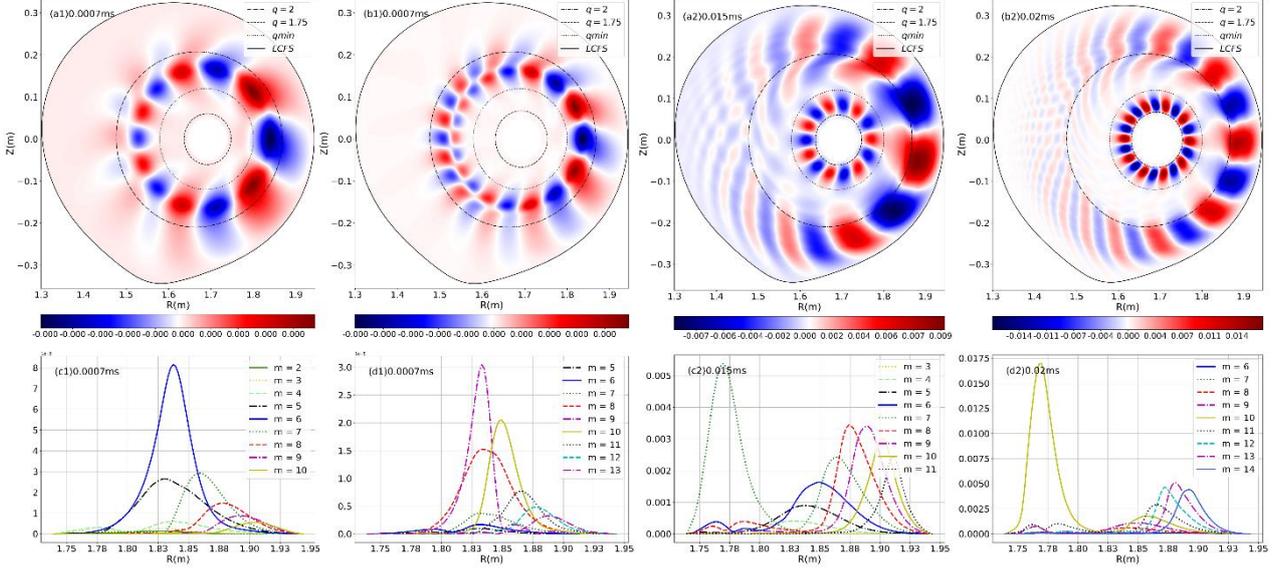

FIG. 5. (a1–d1) are the cross-sectional snapshots at the start of the simulation for $n = 4$ and $n = 6$, showing RSAE-like features; (a2–d2) are the cross-sectional snapshots at linear-growth saturation for $n = 4$ and $n = 6$, which have evolved inward into TAEs.
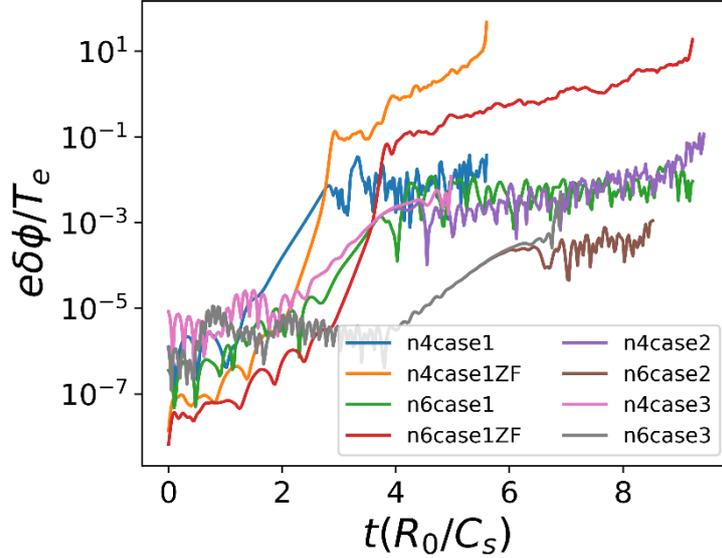

FIG. 6. Effect of the presence or absence of zonal flows (ZF) on the time evolution of the perturbed electrostatic potential $e\delta\phi/T_e$ for different safety-factor profiles. The three cases are: ZF present with the original q profile (case 1), ZF present with the modified q profile (case 2), and ZF absent with the modified q profile (case 3).

Nevertheless, the RSAE-like mode exhibits similar signatures: the mode is radially asymmetric, and this radial localization and symmetry breaking clearly reflect RSAE-like behaviour. One can also see in Fig. 5. (a) and (c) that the inward-radial RSAE-like mode structure undergoes a transition. The frequency spectrum provides further self-consistent verification: the instability from $0.05\,\mathrm{ms}$ to $0.15\,\mathrm{ms}$ is dominated by the RSAE-like mode, with its frequency lying in the gap. At the $0.15\,\mathrm{ms}$ transition from linear to nonlinear phases, not only is there the frequency splitting typical of traditional RSAE, but also strong coupling to TAE, which supports that the RSAE-like mode can similarly transform into a TAE.

We also performed nonlinear simulations for the theoretically subdominant mode $n = 6$, which confirm several conclusions from the $n = 4$ case.

From Fig. 6. (n6case1), the subdominant mode $n = 6$ with linear growth rate γ saturates the RSAE at a relatively low level. The nonlinear growth rate of the zonal flow is again approximately 2γ. Fig. 5. (b1) and (b2) show the cross-sectional perturbed electrostatic potential distributions for the mode-formation, linear-growth and nonlinear-saturation stages from Fig. 6. In Fig. 5. (b1) a RSAE-like mode near q_{min} is clearly visible. mode indeed exhibits smaller continuum gaps and weaker mode amplitude, corresponding to a higher-m RSAE-like mode structure. The comparison in Fig. 6. further shows that the $n = 6$ RSAE-like mode can be maintained for a longer time and produces smaller transport amplitude, which explains the observed behavior.

4.2. Results with the modified magnetic configuration

In the new q profile with $q_{min} \approx 2$, it shows the expected branch crossings in the continuum, producing smaller spectral gaps. It also shows that the mode frequencies lie inside the corresponding continuum gaps, so under these conditions we recover the classical RSAE definition.

Compared with Fig. 6., both $n = 4$ and $n = 6$ now exhibit substantially reduced growth rates and saturation amplitudes, and a longer nonlinear saturation duration. Zonal flows remain a necessary ingredient for nonlinear saturation: without zonal flows RSAE cannot be absorbed effectively, i.e. zonal flows have an even stronger stabilizing role for RSAE than for the RSAE-like mode

A comparison of continuum reveals fewer resonant modes and a narrowed spectral range; the continuum damping acts more effectively, compressing the high-frequency part of the mode spectrum and thereby reducing the overall nonlinear saturation amplitude. This further confirms that the position of q_{min} is a key factor controlling the continuum structure and mode stability.

5. CONCLUSION AND OUTLOOK

This work presents a systematic study of RSAE-like instabilities under reversed-shear conditions on HL-2A using global gyrokinetic simulations that include energetic-particle dynamics. Based on the EFIT equilibrium and measured profiles from discharge #27055, linear multi-toroidal-harmonic calculations identify an $n = 2$ dominated mode that exhibits upward frequency chirping and radial migration; during its evolution toward the TAE band the mode also undergoes structural changes and energy redistribution.

A parameter scan of q_{min} demonstrates that q_{min} critically controls mode existence, frequency, and linear drive: as q_{min} approaches small rational values (e.g., near 2) the linear growth rate and saturation amplitude decrease, continuum damping strengthens, and the mode spectrum compresses. Under elevated-β conditions, a typical evolution with transitions toward BAE/TAE-like behavior is observed.

Nonlinear single-n simulations for secondary unstable modes show that turbulence-driven, zero-frequency zonal flows/fields grow at rates of order 2γ (with γ the linear mode growth rate) and can effectively suppress RSAE-like activity. Energetic-particle transport is weak during the linear phase but increases markedly after mode saturation, chirping, and transition to TAE, indicating that the chirping–migration–transport coupling is a key pathway for fast-particle losses.

Simulations with intentionally modified q-profiles (bringing q_{min} closer to integer values) further corroborate the classical RSAE threshold and reveal smaller saturation amplitudes and stronger continuum damping, underscoring the central role of the q-profile for diagnosing and controlling AE-type instabilities.

Limitations of the present study include insufficient computational resources to perform fully resolved, long-timescale nonlinear simulations of the dominant $n = 2$ mode. Future work should employ longer-duration, higher-fidelity multiscale simulations (including microturbulence[5] and kinetic electrons) and tighter time-resolved comparisons with experiment.

Overall, the study establishes a quantitative workflow from linear identification to nonlinear mechanism verification and provides theoretical and numerical guidance for diagnosing, understanding, and mitigating

AE/RSAE-like instabilities on HL-2A and similar devices, with implications for fast-particle confinement strategies and q-profile optimization in future machines.

ACKNOWLEDGEMENTS

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