

Analysis of the Possible Presence of RSAE-like Modes and RSAEs in HL-2A

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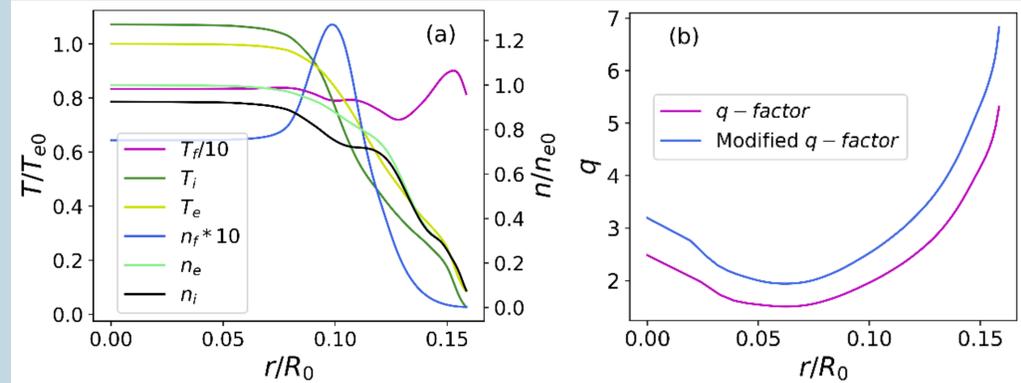
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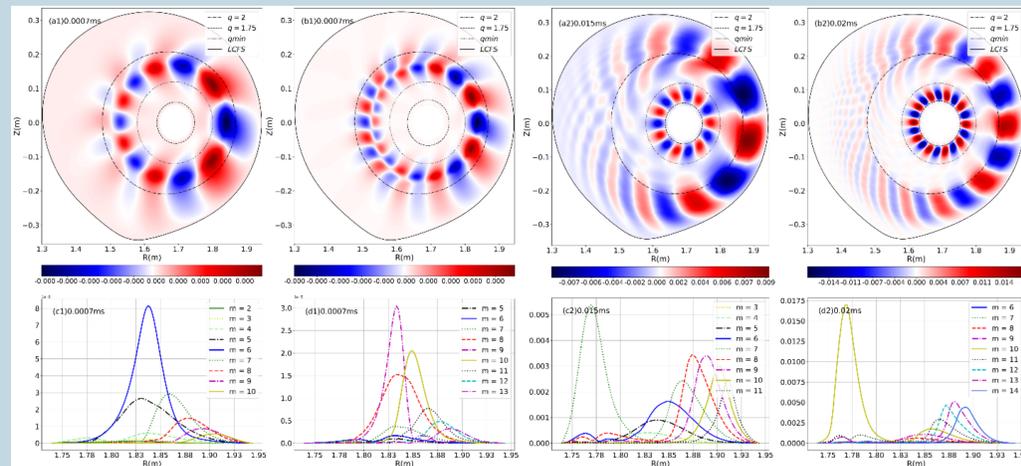
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ABSTRACT

- One of the first systematic gyrokinetic (GTC) studies on HL-2A, targeting a suspected RSAE-like instability in discharge #27055 (H-mode, high β , reverse magnetic shear).
- The observed mode is called “RSAE-like” because it shows clear chirping but differs structurally from classical RSAE.
- Linear multi- n simulations based on experimental profiles identify a dominant mode that chirps into the TAE frequency band and migrates radially.
- Sensitivity scans with varied q -profiles show q -min controls mode existence, frequency, and growth rate; as q -min \rightarrow 2 the linear drive and saturation amplitude drop markedly.
- Nonlinear single- n simulations (on a subdominant n) reveal rapid zonal-flow growth ($\sim 2\times$ the linear mode growth rate) that effectively suppresses RSAE-like activity.
- Energetic-particle transport is weak during the linear phase but increases substantially after saturation, correlating with chirping and structural evolution toward the TAE regime.
- Comparison with other devices finds a universal chirping–migration–transport coupling, while HL-2A shows specific dependencies on q -profile, β , and energetic-particle distribution.
- The sequential workflow—experiment-based linear mode selection followed by nonlinear validation—provides a quantitative framework for diagnosing and controlling AE-like instabilities on HL-2A and guides future experiment–model integration.



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.

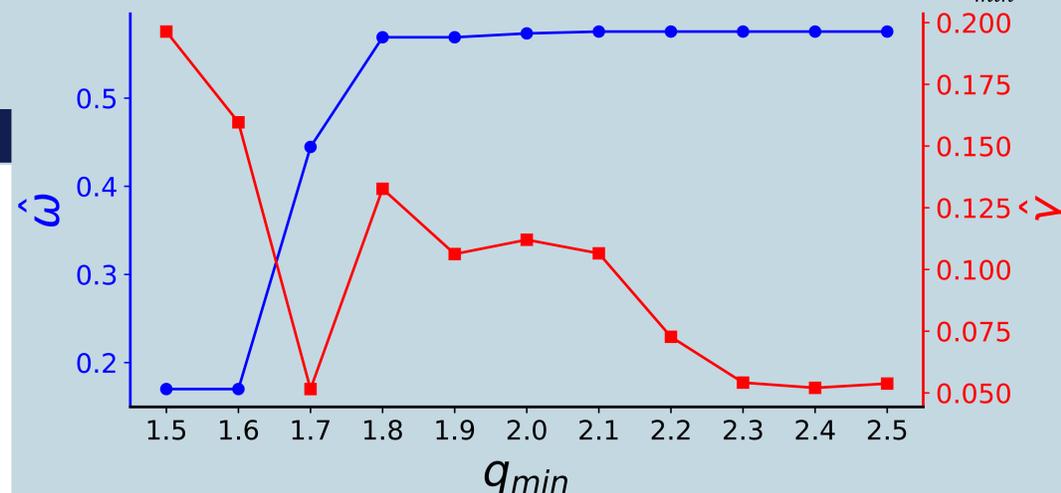


(a1–d1) are the cross-sectional snapshots at the start of the simulation for $n = 4$ and $n = 6$, showing RSAE-like features; (a2–d2) are the cross-sectional snapshots at linear-growth saturation for $n = 4$ and $n = 6$, which have evolved inward into TAEs. The rate of the (2,3) mode on q_{\min} .

NONLINEAR RESULT

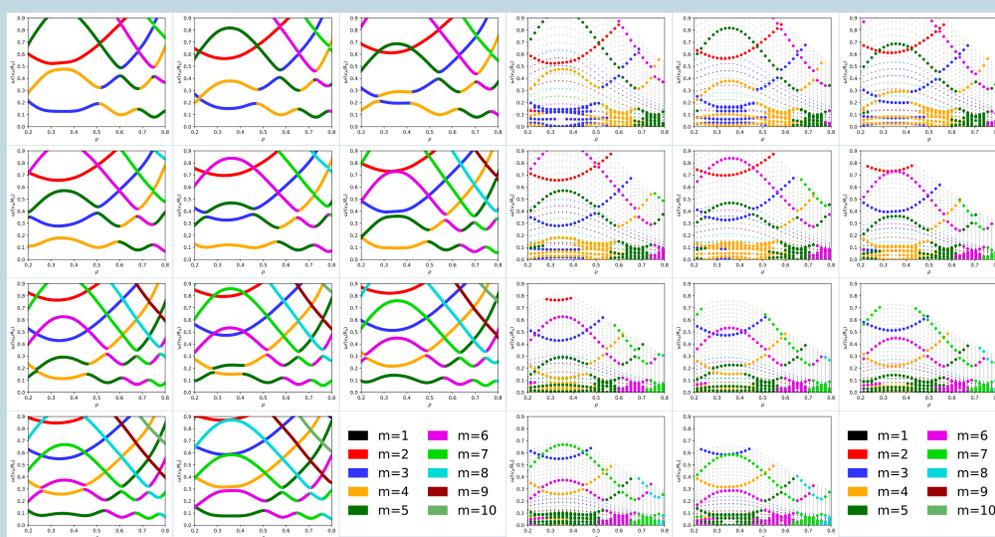
- * Zonal structures: zero-frequency zonal flows/fields grow at rates $\approx 2\gamma$ ($\approx 2\times$ the linear mode growth rate) \rightarrow strong suppression of the mode.
- * Mode saturation: RSAE-like modes saturate at reduced amplitude when zonal regulation is strong.
- * Energetic-particle transport: weak during the linear phase, but rises sharply after mode saturation, chirping, and transition to TAE.
- * Mode transition: RSAE-like activity can evolve into TAE, enhancing fast-ion redistribution and losses.
- * q -profile effect: moving q_{\min} closer to an integer \rightarrow stronger continuum damping, lower saturation amplitude, and improved mode control.

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



ACKNOWLEDGEMENTS

Support from Fudan University; the Boling Class (Nankai University) and the China Institute for Advanced Study in Nuclear Energy and Safety; HL-2A data from the Southwest Institute of Physics (CNNC); computing resources from DOE/NERSC; and help from senior colleagues.



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.

LINEAR ANALYSIS

- * Dominant mode: $n = 2$ RSAE-like instability — upward frequency chirping and radial migration.
- * Spectral evolution: mode evolves into the TAE band with clear structural change and energy redistribution.
- * q_{\min} dependence: as q_{\min} approaches small rationals (e.g. near 2) \rightarrow linear growth rate \downarrow , saturation amplitude \downarrow , continuum damping \uparrow , spectrum compressed.
- * High- β effects: at elevated β observe atypical evolution and transitions toward BAE/TAE-like behavior.
- * Continuum interaction: mode frequency and radial localization are constrained by Alfvén continuum gaps and branch crossings.