THE RESEARCH OF THE STABILITY OF REVERSED SHEAR ALFVÉN EIGENMODES EXCITED BY ENERGETIC PARTICLES IN HL-2A

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1. ABSTRACT

This work represents a ground-breaking investigation into the stability of suspected Reversed Shear Alfvén Eigenmodes (RSAEs) in the HL-2A device using the Gyrokinetic Toroidal Code (GTC) [1]. It is the first study to employ GTC on HL-2A RSAE-like instability, yielding device-specific insights that are crucial for understanding and controlling Alfvénic instabilities in fusion plasmas. The study not only examines multiple toroidal mode number scenarios alongside single mode cases but also uncovers unique phenomena such as the identification of the most unstable modes ($n = 4$ and $n = 6$), the suppression of these modes by Zonal Flow (ZF), and the transition from suspected RSAE to Toroidal Alfvén Eigenmode (TAE). Moreover, it reveals a critical correlation between the generation location of suspected RSAEs and the position of rational surfaces, while providing a detailed analysis of energetic particle transport within the mode dynamics. These results have significant implications for both experimental design and theoretical advancements in fusion research.

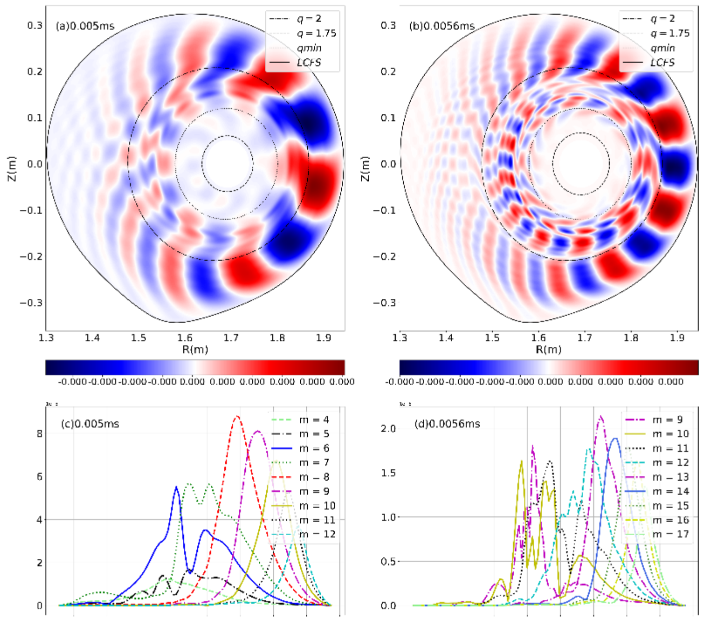

FIG. 1. Poloidal contour plots of perturbed electrostatic potential eδϕ/T, case n=4 [panel (a)], case n=6 [panel (b)] and their corresponding poloidal Fourier decomposition [lpanel (c)(d)]

2. BACKGROUND AND MOTIVATION

The reversed shear configuration helps enhance the overall confinement of the device. In HL-2A, the reversed shear configuration creates conditions that are particularly conducive to the excitation of RSAEs. GTC simulations on devices such as DIII-D [2] and EAST have successfully explained the physical mechanisms underlying experimental observations. Fusion plasmas are inherently complex, with interactions between energetic particles and the background magnetic field leading to various instabilities [3]. RSAEs, in particular, can be driven by the resonant interaction between fast ions and Alfvén waves. The HL-2A device, with its distinct reversed shear profile, offers a unique environment for studying these interactions. In the future, HL-3, as an upgraded device of HL-2A, may also adopt a reversed shear configuration.

3. SIMULATION SETUP

In our research, the kinetic EFIT magnetic equilibrium geometry and plasma profiles are adopted from HL-2A shot #27055 at 602 ms, which is a H-mode discharge at high β. The safety factor q profile exhibits a reversed shear configuration with a minimum value of $q_{\min} = 1.52$ near $\rho = 0.38$, where RSAE can be driven by fast ions. The GTC code [1] used in this study is a global toroidal gyrokinetic code employing gyrokinetic ions and drift-kinetic electrons. The simulation time step is set to 10^{-9} s to resolve high-frequency Alfvén eigenmodes and ensure numerical stability. In nonlinear electromagnetic simulations of suspected RSAE, convergence studies determine that 5×10^4 unstructured perpendicular grids with 1000 particles per cell per species are adequate. In all simulations, all poloidal harmonics m are retained while using Fourier filtering to isolate specific toroidal modes. The device's Alfvén continuum is computed by ALCON [4] to verify the characteristic features of RSAEs. The study examines the influence of ZF on suspected RSAE stability. A detailed examination of the transport properties [5] of energetic particles in the presence of suspected RSAEs is performed.

4. KEY FINDINGS

The multiple modes simulations reveal that the most unstable toroidal mode numbers are $n = 4$ and $n = 6$. These modes exhibit the highest growth rates. In single mode simulation, the growth rate of suspected RSAE exhibits a twofold relationship with the growth rate of ZF, which is consistent with both theoretical and experimental results. ZF is observed to effectively suppress RSAE-like activity. Figure 1 shows the transition of suspected RSAE from the linear growth phase to the nonlinear saturation stage. A strong correlation is found between the generation location of suspected RSAEs and the positions of rational surfaces within the plasma. The computation of the Alfvén continuum in Figure 2 confirms the RSAE characteristics and documents a clear transition from RSAE to TAE. The analysis of energetic particle transport demonstrates that the interaction between these particles and the excited modes significantly influences mode stability. They are also an important factor in causing the mode transition.

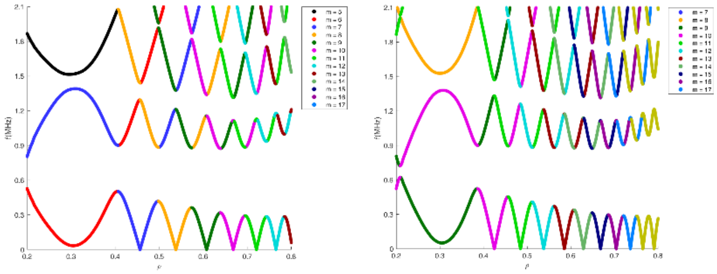

FIG. 2. Alfven continuum of n=4 (left) and n=6(right) . The colored lines represent various poloidal harmonics

5. IMPLICATIONS AND FUTURE OUTLOOK

The device-specific insights gained from HL-2A can directly influence the design and operational strategies of current and future fusion experiments, like HL-3. The successful application of GTC and the coherence of a kinetic-MHD model set new benchmarks for theoretical investigations [6] into Alfvén eigenmodes. Our work also suggests several promising directions for future research. Expanding the analysis into the late nonlinear regime for long-term evolution of these modes could yield further insights into the stability of fusion plasmas.

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