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Comprehensive analytical and numerical study of beam-driven sub-cyclotron frequency Alfvén eigenmodes in spherical tokamaks

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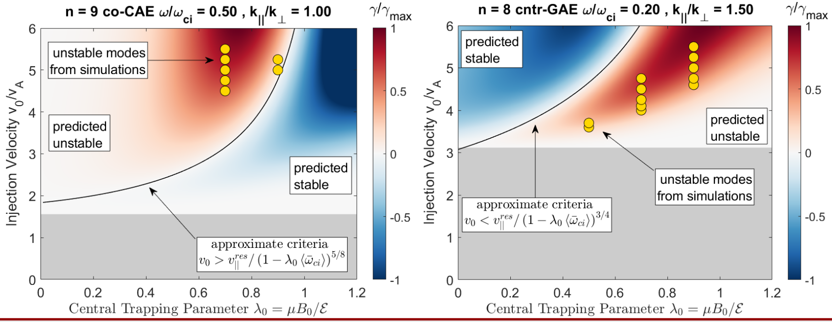
Main Highlights

New analytic stability conditions agree with 3D simulations

- Large set of 3D self-consistent simulations reveals complex dependence of CAE/GAE stability on the injection velocity and central pitch of fast ions with $f_{NBI}(v,\lambda) \sim e^{-(\lambda-\lambda_0)^2/\Delta\lambda^2}/(v^3+v_c^3)$
- Numerical integration of analytic expressions for fast ion drive yields theoretical predictions for stability which agree with simulations
  - Approximate criteria for net fast ion drive can be derived for distributions with realistic width in velocity space ($\Delta\lambda \approx 0.3$)

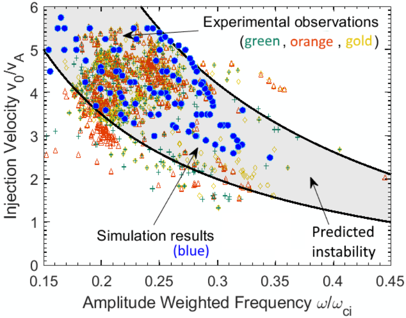


Experiment, theory, and simulation comparison

- Cross comparison for cntr-GAEs shows excellent agreement against vast experimental database
- Net fast ion drive determines range of allowed v_0/v_A for given ω/ω_{ci}:

$$\frac{\langle\omega_{ci}\rangle}{\omega} - 1 < \frac{v_0}{v_A} < \frac{\langle\omega_{ci}\rangle/\omega - 1}{\left(1 - \lambda_0\langle\bar{\omega}_{ci}\rangle\right)^{3/4}}$$

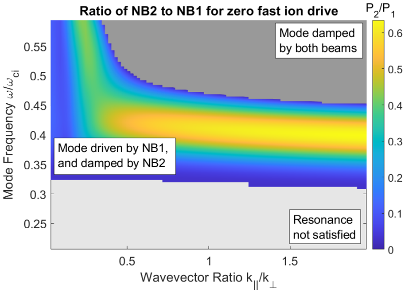
- Previous theory results assuming $f_{NBI}(\lambda) \sim \delta(\lambda - \lambda_0)$ fail to correctly predict unstable spectra in experiments



Green, orange, gold: experiment
Blue circles: simulation results
Shaded region: analytic theory

Proposed techniques for multi-beam control of GAEs/CAEs

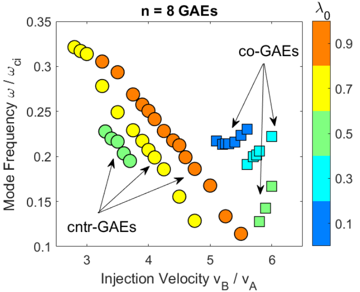
- Theory predicts that additional beams will **damp** the modes if injected appropriately
  - Must choose geometry (λ_0) or voltage (v_0/v_A) to coincide with fast ion damping
- Already demonstrated experimentally for cntr-GAEs during early NSTX-U operations
- Multi-beam stabilization shows how to control the modes while **increasing** beam power
  - Enables efficient plasma heating scenarios that avoid CAE/GAE-induced enhanced electron transport!



Theoretical predictions of fractional power necessary in off-axis beam (NB2) to stabilize cntr-GAEs driven by on-axis beam (NB1) in NSTX-U

Energetic-particle-modified GAEs

- Hybrid simulations show that fast ions can strongly modify GAEs in ST plasmas heated by strong NBI
  - Challenges assumption that GAEs are well described by perturbative MHD
- Frequency changes significantly and continuously with v_0/v_A
  - Mostly due to changes in EP phase space, **not** EP-induced changes to equilibrium
- Mode structure does not change substantially with frequency
- Results may indicate a new, high frequency energetic particle mode



EP-GAE frequency dependence on v_0/v_A. Color denotes the central pitch $\lambda_0 = \mu B_0/\mathcal{E}$ of the beam distribution used in each simulation. On-axis $f_{ci} = 2.4$ MHz.