Simulations of NBI-driven Global Alfven Eigenmodes in NSTX

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Motivation:

- Multiple sub-cyclotron frequency modes are observed in NSTX during NBI injection.
- CAE and GAE modes are predicted to be driven unstable by super Alfvenic NBI ions with V_b~$3V_A$ (80 keV) through the Doppler shifted cyclotron resonance.
- Strong anisotropy in the fast-ion pitch-angle distribution provides the energy source for these instabilities.
- New observations of sub-cyclotron frequency modes during NBI injection show the spectrum line intersections, corresponding to GAE dispersion (with q-profile relaxation), and nonlinear evolution of GAE spectrum.
- Both CAE and GAE modes are observed.
- Numerical simulations are needed to include: self-consistent anisotropic equilibrium, FLR effects, thermal ion and nonlinear effects.

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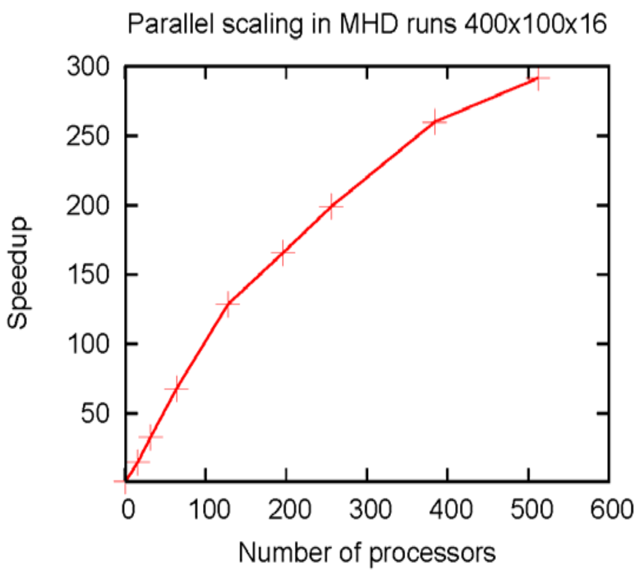
HYM – Parallel Hybrid/MHD Code

HYM code developed at PPPL and used to investigate kinetic effects on MHD modes in toroidal geometry (FRCs and NSTX)

- 3-D nonlinear.
- Three different physical models:
  - Resistive MHD & Hall-MHD.
  - Hybrid (fluid electrons, particle ions).
  - MHD/particle (one fluid thermal plasma, + energetic particle ions)[1]
- Full-orbit kinetic ions.
- For particles: delta-f / full-f numerical scheme.
- Parallel (3D domain decomposition, MPI)[2].

[1]Beam ions: $V_0 > V_A$, large Larmor radius $\rho_i / L \sim 0.1\text{-}0.3$.
High-frequency modes: $\omega \sim \omega_{ci}$

[2]Simulations are performed at NERSC.



N_{procs}

New MPI version of HYM shows good parallel scaling up to 500 processors for production-size jobs, and allows high-resolution nonlinear simulations.

Self-consistent anisotropic equilibrium the energetic NBI ions in NSTX

Grad-Shafranov equation for two-component plasma: MHD plasma (bulk) and fast ions

$$\frac{\partial^2\psi}{\partial z^2} + R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial\psi}{\partial R}\right) = -R^2 p' - HH' - GH' + RJ_{i\phi}$$

$$\mathbf{B} = \nabla\phi\times\nabla\psi + h\nabla\phi$$

$$h(R,z) = H(\psi) + G(R,z)$$

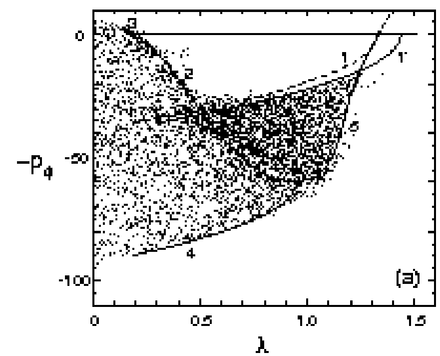
$$\mathbf{J}_{ip} = \nabla G\times\nabla\phi \quad , \; G - \text{poloidal stream function}$$

Self-consistent MHD + fast ions coupling scheme

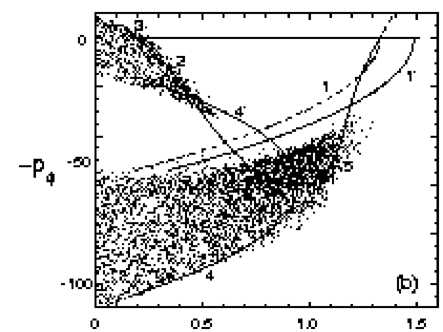
Background plasma - fluid: $\rho\frac{d\mathbf{V}}{dt} = -\nabla p + (\mathbf{j} - \mathbf{j}_i)\times\mathbf{B} - n_i(\mathbf{E} - \eta\mathbf{j})$

Fast ions – delta-f scheme: $F_0=F_0(\varepsilon,\mu,p_\varphi)$, where μ is calculated up to 1st order in ρ_i /L; realistic F_0 to match the distribution functions computed from the TRANSP code:

-The prompt-loss condition, anisotropy, the large Larmor radius of the beam ions and the strong pitch-angle scattering at low energies have been included in order to match the distribution functions computed from the TRANSP code.

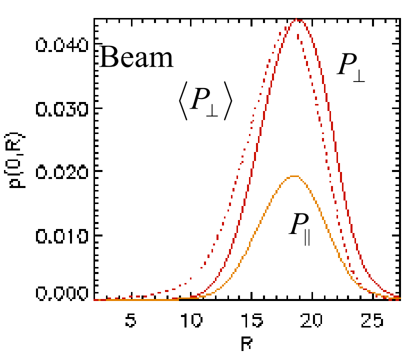


$V_0 = 2V_A$



$V_0 = 3V_A$

$\lambda = \mu B_0 / \varepsilon$



Strong modifications of equilibrium profiles due to beam ions: more peaked current profile, anisotropic pressure, increase in Shafranov shift and reduction of q_{axis} – indirect effect on stability.

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3D simulations of energetic ion-driven instabilities in NSTX

Linearized delta-f simulations

- Low-n simulations (n=1-6) show instability of Global Alfven Eigenmode (GAE) with large $k_{||}$, and significant compressional component $\delta B_{||} \approx 1/3\, \delta B_{\perp}$.

  For n=4 and m=-2, $\gamma = 0.005\omega_{ci}$ and $\omega = 0.3\omega_{ci}$ for n_b=3%
  $\gamma = 0.016\omega_{ci}$ and $\omega = 0.3\omega_{ci}$ for n_b=5% (E=80keV)

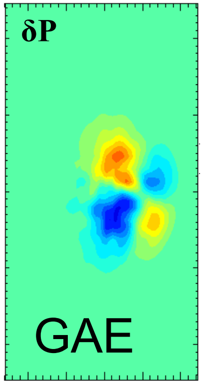
- Hybrid simulation with n=8 show weakly unstable CAE mode with m=8-10, $\omega = 0.4\omega_{ci}$, $\gamma \approx 0.001\omega_{ci}$, and $\delta B_{||} > \delta B_{\perp}$

- GAE modes are more unstable than CAE (agrees with analytical calculations) with $\gamma/\omega \sim n_b/n_0$.

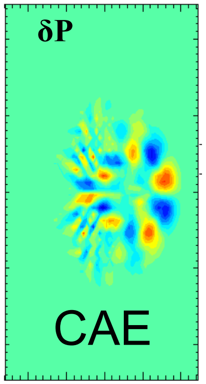
- Main damping mechanism for GAE is continuum damping (modeled in HYM with artificial viscosity): $\gamma_d/\omega \sim (r/r_{res})^{2m+\delta}$

- Simulations with different n show that most unstable modes have (n-m)~6-7, ie same $k_{||}$.

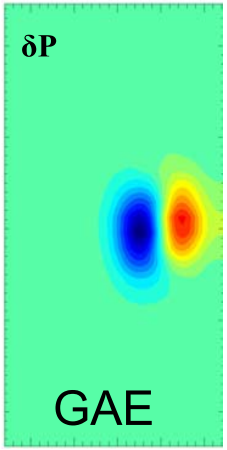
- Modes with larger-m have smaller radial extent.



n=4 (m=-2)



n=8



n=6(m=-1)

Low-*n* most unstable modes have a character of GAE modes

- Modes with 2<*n*<7 are unstable.
- For each *n,* several *m* are unstable with large $k_{\|}$ and *nm*<0.
- Localized near magnetic axis.
- Large $\delta B_{\perp}$ component.

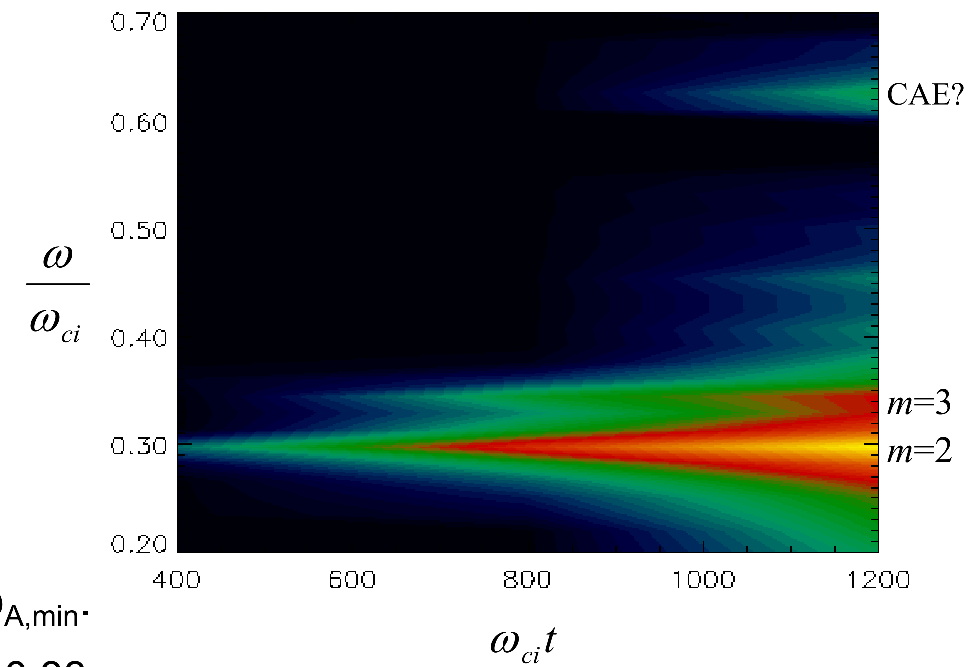
- observed features agree with that of GAE mode, which exists just below the lower edge of the Alfven continuum [Appert et al.,1982].

GAE modes are primarily cylindrical and localized radialy near min(ω_A) with $\omega < \omega_{A,min}$.

For n=4, m=-2 case $\omega/\omega_{ci}=0.3 < \omega_A/\omega_{ci}=0.33$.

$$\omega \approx \pm \frac{V_A}{R_0}\left(\frac{m}{q_0} - n\right)$$

Simulations with *n*=4



Resonant condition for GAE instability

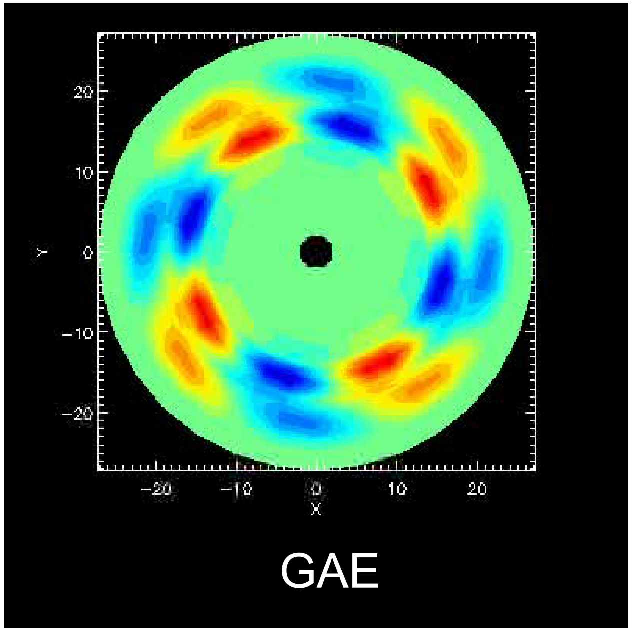
Resonant beam ions satisfy condition:

$$\omega - k_{\|}V_{\|} - \omega_{ci} \approx 0$$

$$\omega \approx k_{\|}V_{\|}$$

In the simulations: $V_{\|} > 0$ and $\omega/k_{\|} < 0$.

For ω= 0.3-0.4ω_{ci} and $k_{\|}V_A$ ~0.3, the resonant particles will have $V_{\|}$ ~2V_A $\rightarrow$ significant fraction of beam ions can be in resonance.



Contour plot of perturbed fluid pressure at equatorial plane.

Nonlinear simulations (GAE instability)

3D nonlinear hybrid simulations for given toroidal mode number

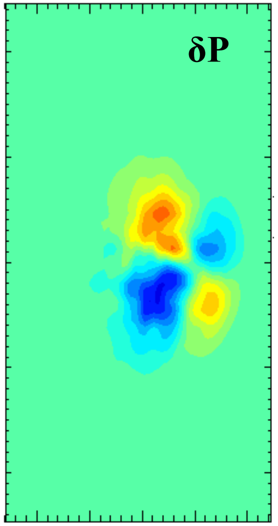
- Nonlinear results (n_b=5%) show saturation of instability at relatively low amplitudes:

  $\delta P \sim 0.8 \cdot 10^{-3}$
  $\delta V_R \sim 6 \cdot 10^{-3}$
  $\delta V_Z \sim 6 \cdot 10^{-3}$
  $\delta V_\varphi \sim 10^{-3}$

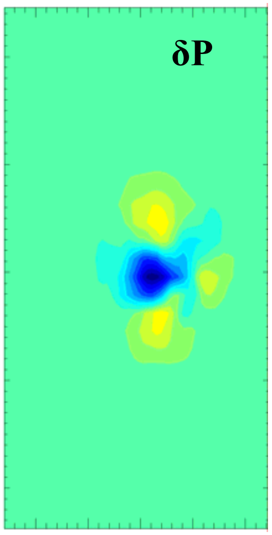
- Most unstable mode changes nonlinearly from n=4 m=-2 mode to (4,-3) mode.

- Poloidal mode structure is complicated: several modes with different poloidal mode number have comparable amplitudes.

- Initial fully nonlinear simulations (many-*n*) show dominant *n*=3 instability.



Linear mode structure, n=4, m=-2



Nonlinear mode structure n=4, m=-3 (at saturation)

Conclusions

- Nonlinear 3D HYM code has been modified for ST geometry and parallelized.
- Grad-Shafranov solver for general case of the two component plasma: MHD plasma with $p=p(\psi)$, plus energetic ions with realistic (anisotropic) distribution.
- Simulations show that for large injection velocities, and strong anisotropy in the pitch-angle distributiom, many Alfven modes can be excited: GAE modes for $2<n<7$, and CAE modes for larger *n.*
- Instabilities are excited via Doppler-shifted resonance with NBI ions.
- GAE instability saturates at low amplitude, for given-n several poloidal modes are excited with comparable amplitudes in nonlinear regime.