Nonlinear Simulations of NBI-driven GAE modes 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 $V_b \sim 3V_A$ (80 keV) through the Doppler shifted cyclotron resonance.
• Strong anisotropy in the fast-ion pitch-angle distribution provides the energy source for these instabilities.
• 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, parallel (3D domain decomposition, MPI).
- Physics model: MHD/particle (one fluid thermal plasma + energetic particle ions)
- Full-orbit kinetic ions using delta-f / full-f numerical scheme.

Model

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

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

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

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

$$\mathbf{J}_{ip} = \nabla G\times\nabla\phi$$, G – poloidal stream function

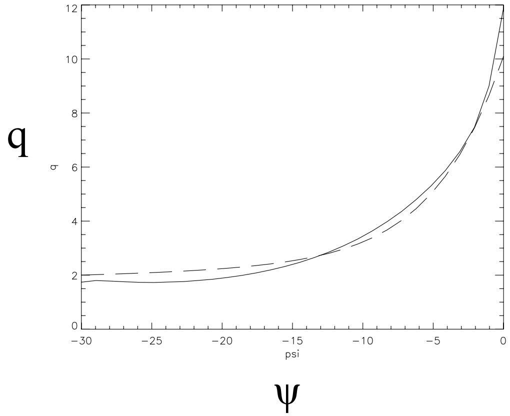
Self-consistent MHD + fast ions coupling scheme

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

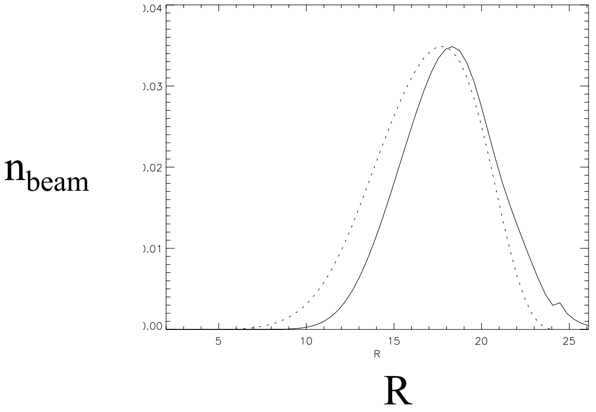
Fast ions – delta-f scheme: $F_0=F_0(\varepsilon,\mu,p_\varphi)$, where μ is calculated up to 1st order in ρ_i /L; realistic F_0 to match the distribution functions computed from the TRANSP code.

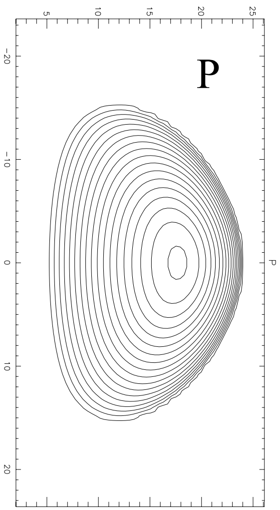
Plasma parameters and profiles are matched to NSTX shot #114147 (TRANSP)

q-profile vs poloidal flux

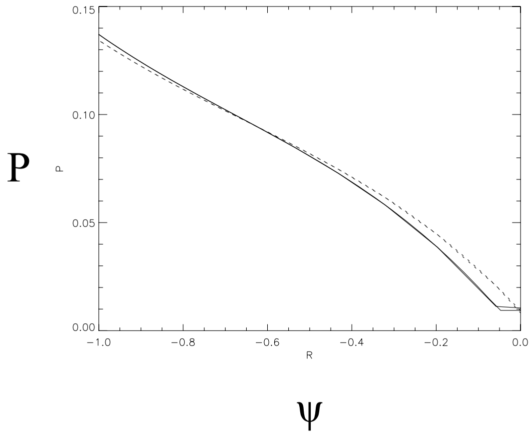


Beam density vs major radius

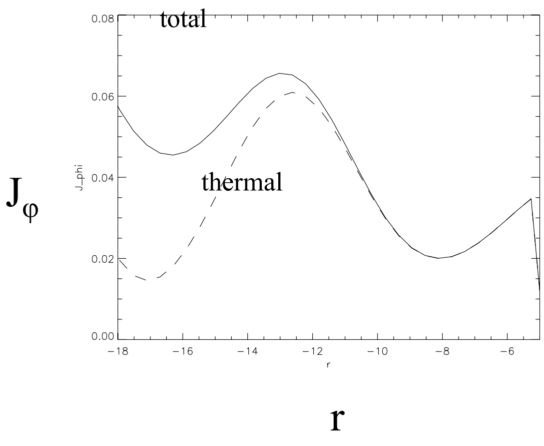




Pressure profile vs poloidal flux

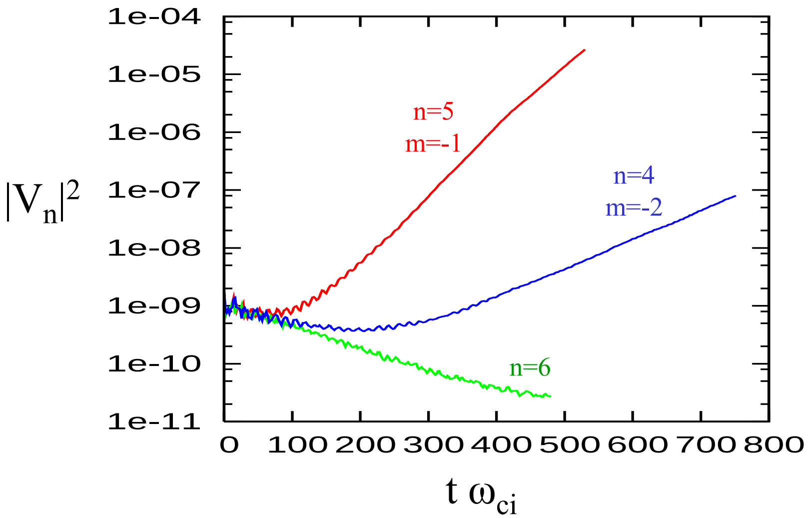


Toroidal current vs minor radius



3D simulations of energetic ion-driven instabilities in NSTX

- Growth rates of unstable modes are very sensitive to details of distribution function (pitch-angle); equilibrium profiles are not.
- Most unstable mode toroidal number shifts to larger n for larger q_0: n=5, m=-1

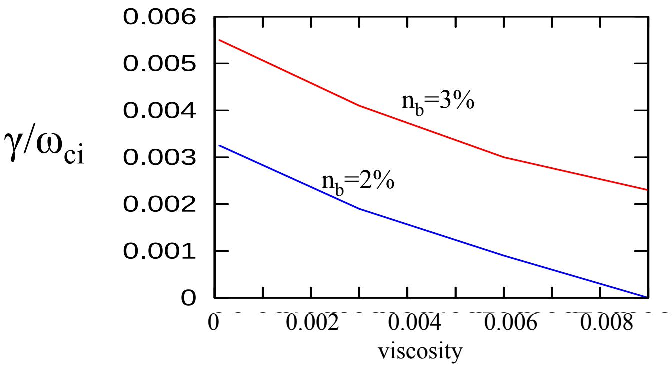


γ_4= 0.005ω_{ci} and ω= 0.3ω_{ci}
γ_5= 0.014ω_{ci} ω= 0.3ω_{ci}

$$k_{\parallel} = \frac{\omega_{ci} - |\omega|}{v_{\parallel}}$$

Observed features agree with that of GAE mode, which exists just below the lower edge of the Alfven continuum:

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

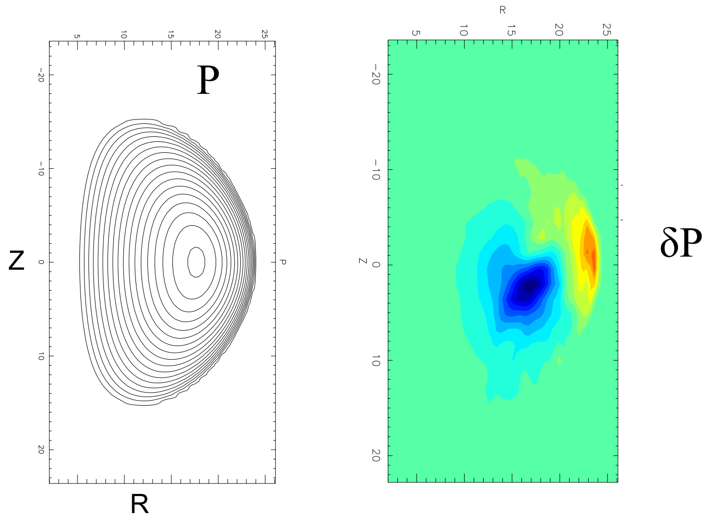


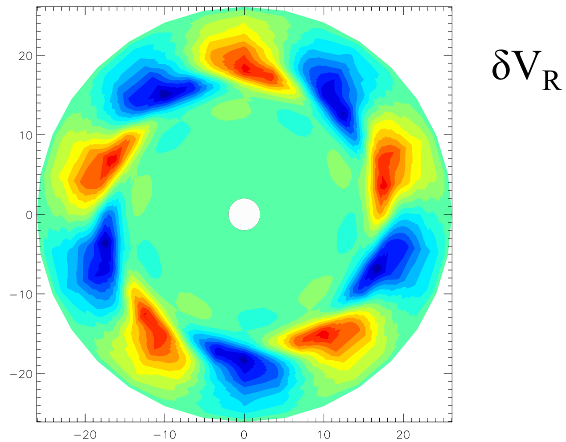
Dependence of the linear growth rate on viscosity.

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

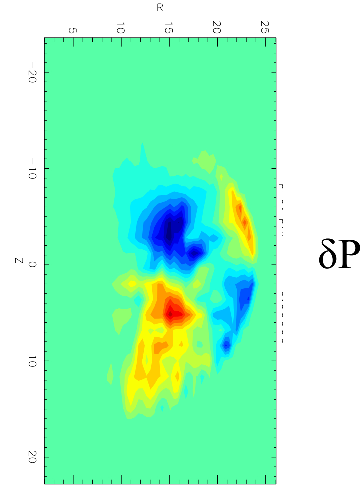
Mode structure (equilibrium #114147)

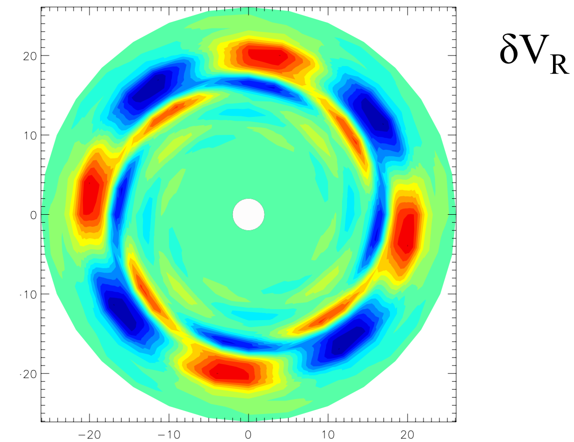
n=5 m=-1





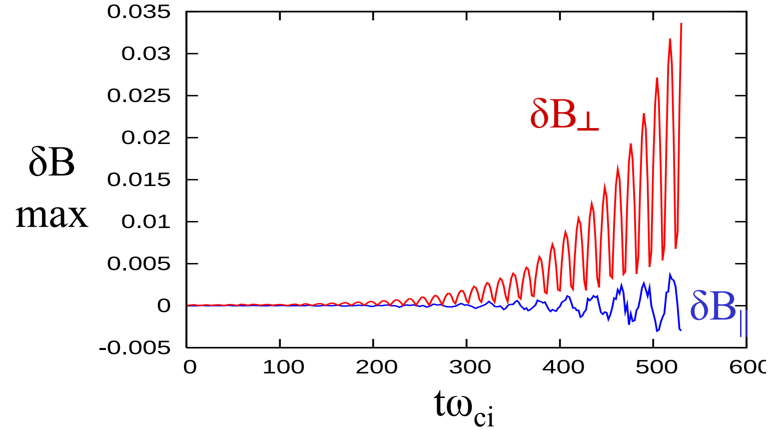
n=4 m=-2

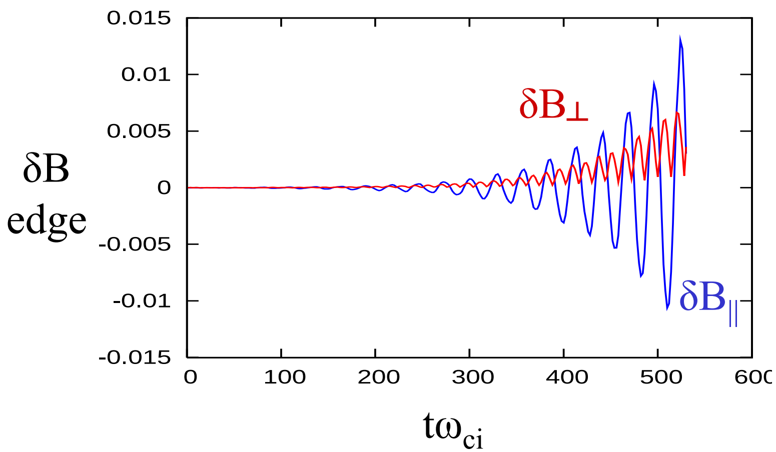




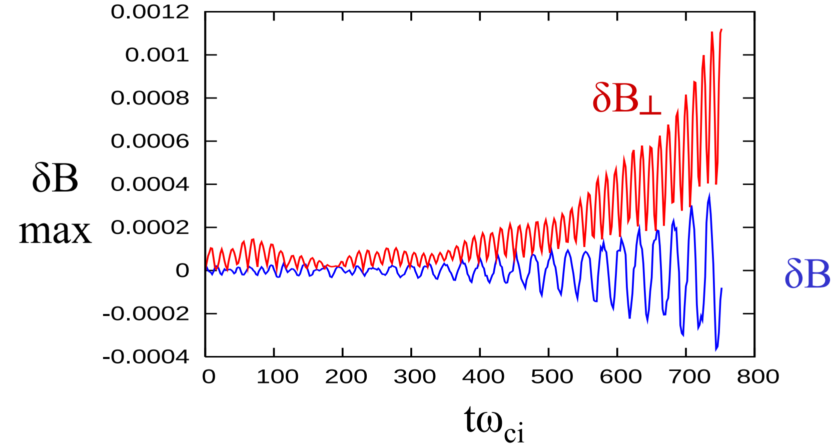
Magnetic mode structure

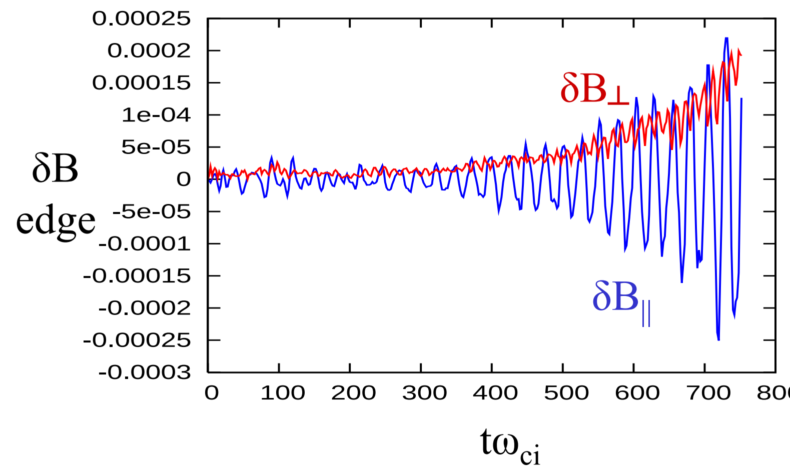
n=5 m=-1





n=4 m=-2





At peak amplitude $\delta B_{\parallel} \approx 1/3\ \delta B_{\perp}$, but at the edge there is significant compressional component $\delta B_{\parallel} > \delta B_{\perp}$.