Numerical Simulations of NBI-Driven Sub-Cyclotron Frequency Modes using the HYM Code

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HYM code has been modified to include more accurate description of the beam induced current

- The Ohkawa current correction is needed in order to match TRANSP beam ion density and current profiles. Correction is significant with $(1-Z_b/Z_{eff}) \sim 0.4$.

- Generalized Grad-Shafranov equation for fast ion-thermal plasma system [Belova et al., PoP 2003] is missing expression for parallel current.

- HYM code has been modified to include more accurate description of the beam induced current: $J_{beam} \rightarrow J_{beam} - (Z_b/Z_{eff})\, J_{beam\ ||}$

Self-consistent MHD + fast ions coupling scheme

Thermal plasma - fluid:

$$\rho \frac{d\mathbf{V}}{dt} = -\nabla p + (\mathbf{j} - \mathbf{j}_b) \times \mathbf{B} - n_b (\mathbf{E} - \eta \mathbf{j})$$

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{j}$$

$$\mathbf{B} = \mathbf{B}_0 + \nabla \times \mathbf{A}$$

$$\partial \mathbf{A} / \partial t = -\mathbf{E}$$

$$\mathbf{j} = \nabla \times \mathbf{B}$$

$$\partial p^{1/\gamma} / \partial t = -\nabla \cdot (\mathbf{V} p^{1/\gamma})$$

$$\partial \rho / \partial t = -\nabla \cdot (\mathbf{V} \rho)$$

Fast ions – particles:

$$F_0 = F_0(\varepsilon, \mu, p_\phi)$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = \mathbf{E} - \eta \mathbf{j} + \mathbf{v} \times \mathbf{B}$$

ρ, **V** and *p* are thermal plasma density, velocity and pressure, n_b and $\boldsymbol{j_b}$ are fast ion density and current, $n_b << n$ – is assumed.

Self-consistent MHD + fast ions - Equilibrium

Assuming **V**=0:

$$0 = -\nabla p + (\mathbf{J} - \mathbf{J}_b) \times \mathbf{B}$$

$$\nabla \times \mathbf{B} = \mathbf{J}$$

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

$$\mathbf{J}_b = \nabla G \times \nabla\phi + \mathbf{J}_{b\phi}$$

$$\text{where } h(R,z) = H(\psi) + G(R,z)$$

Grad-Shafranov equation for two-component plasma: thermal plasma and fast ions [Belova et al., PoP 2003]

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

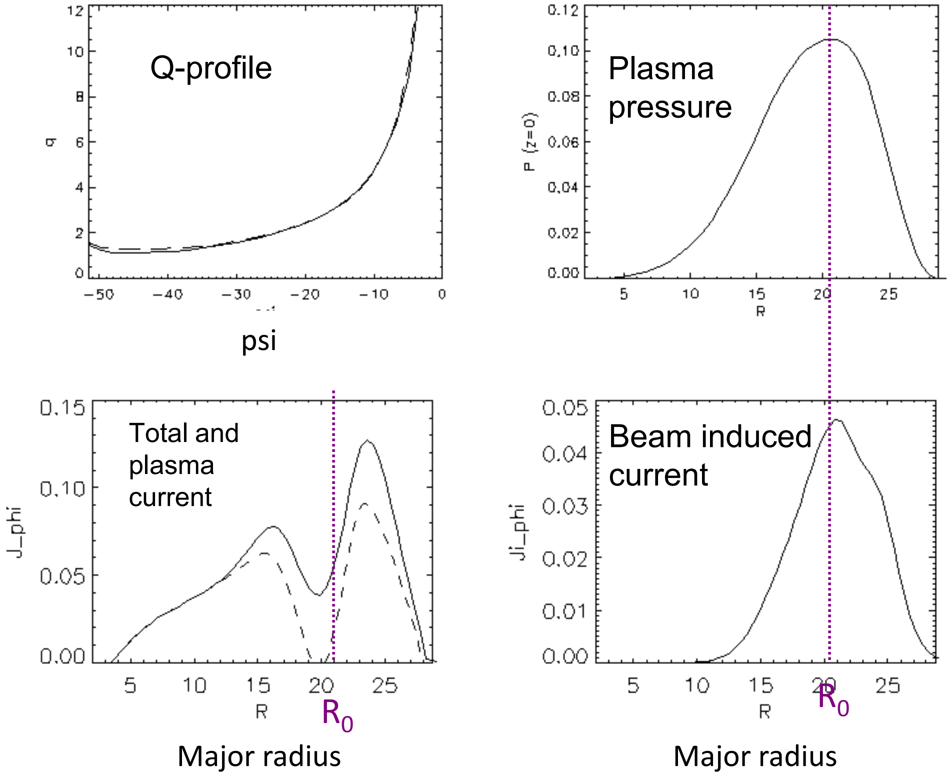
For specified flux functions $H(\psi)$, $p(\psi)$ (found from a fit to experimental profiles) and fast ion distribution function, parallel thermal plasma current is given by:

$$J_{th\,\|} = -BH' - p'(H+G)/B$$

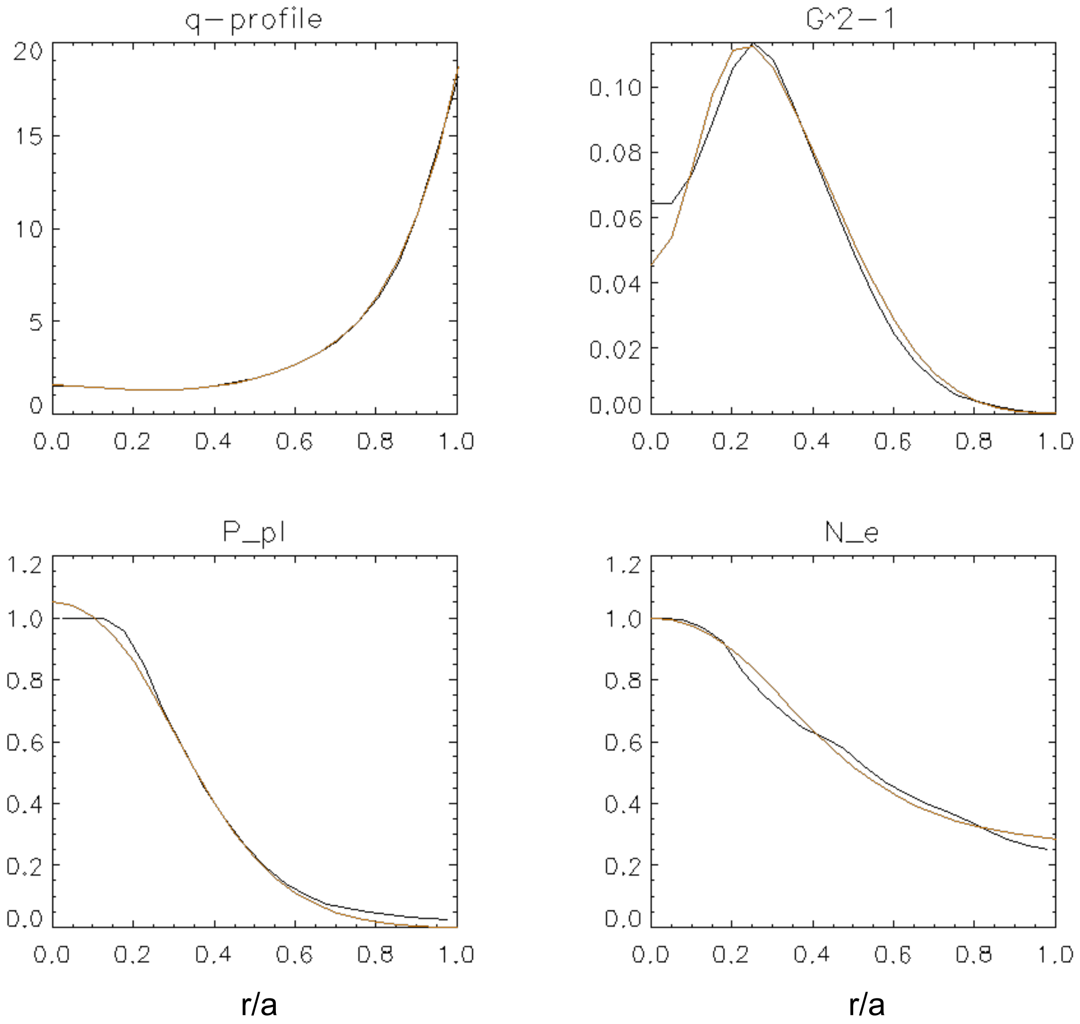
HYM simulations for NSTX shot 135419

- HYM code has been modified to include more accurate description of the beam induced current:

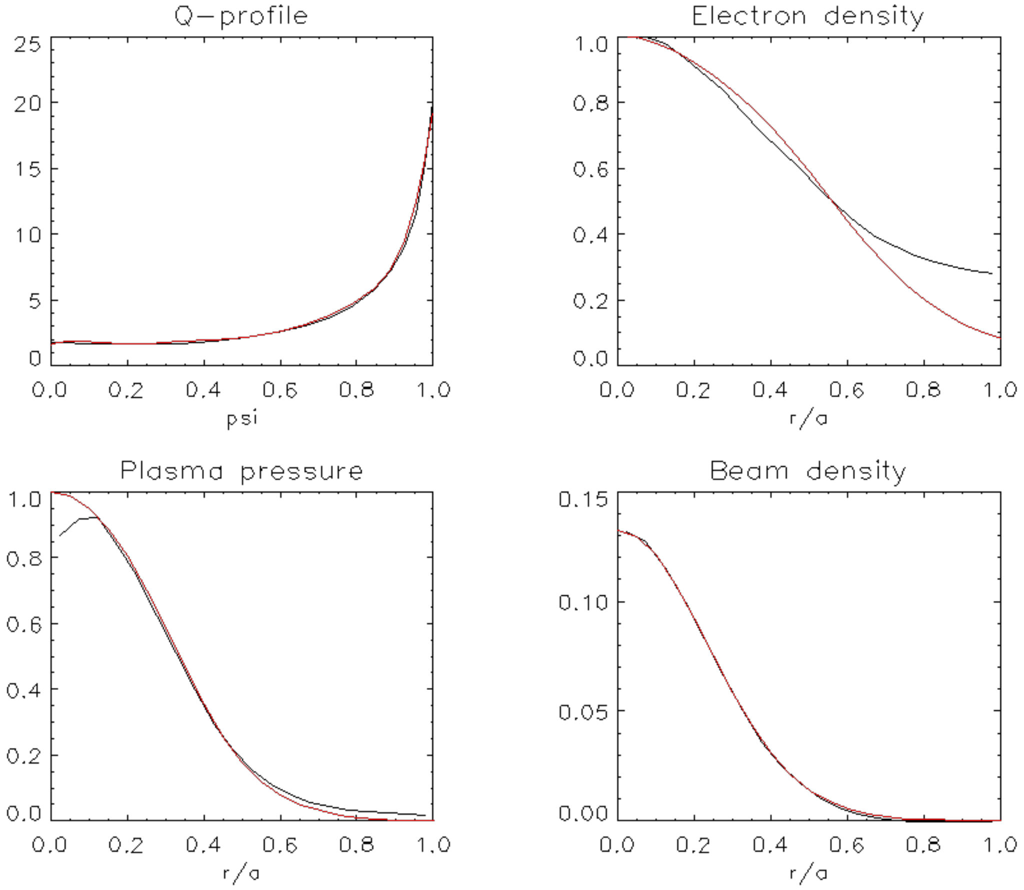
  $\delta J_b \rightarrow \delta J_b - (Z_b/Z_{eff})\, \delta J_{b\,||}$



Equilibrium profiles NSTX shot #135419



Plasma parameters and profiles are matched to NSTX shot #130705



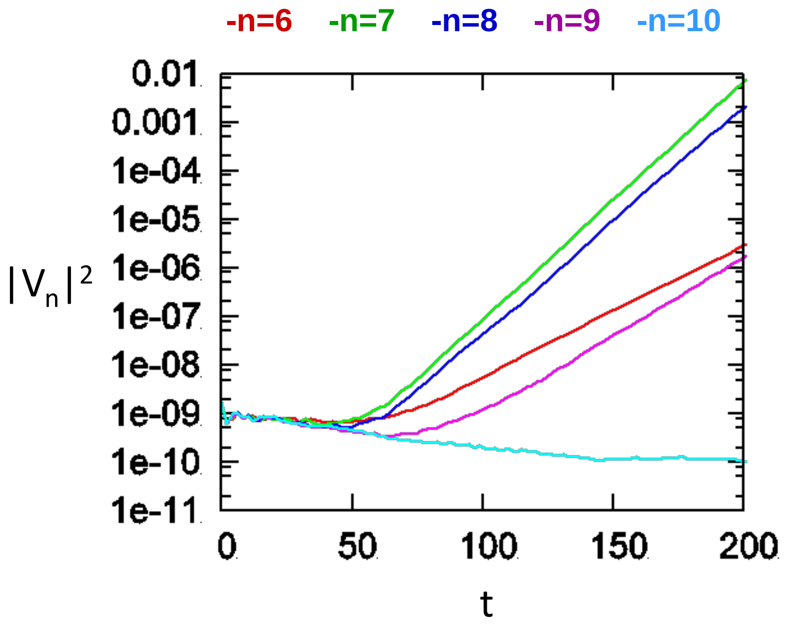
HYM simulations comparison with experimental results for NSTX shot#135419 [E. Fredrickson et al]

- Several modes are unstable with toroidal mode numbers n=6 - 9 and frequencies f=0.4-0.8MHz (plasma frame) compared to experimental results of n=9 - 11, and f=0.8-1MHz.

- GAE modes.

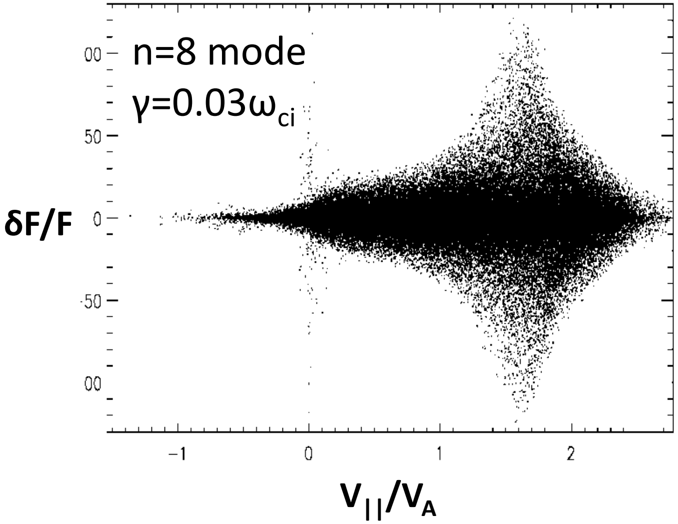
- Linear growth rate as inferred from observed growth time $\gamma \approx 0.005\omega_{ci}$ compared to numerically calculated $\gamma \approx 0.02\, \omega_{ci}$ (no damping $\gamma_d = 0$).

- Similar mode structure.



Time evolution of kinetic energy from 5 linearized simulations with n=6-10 (zero damping parameter).

Phase-space plots: resonant condition

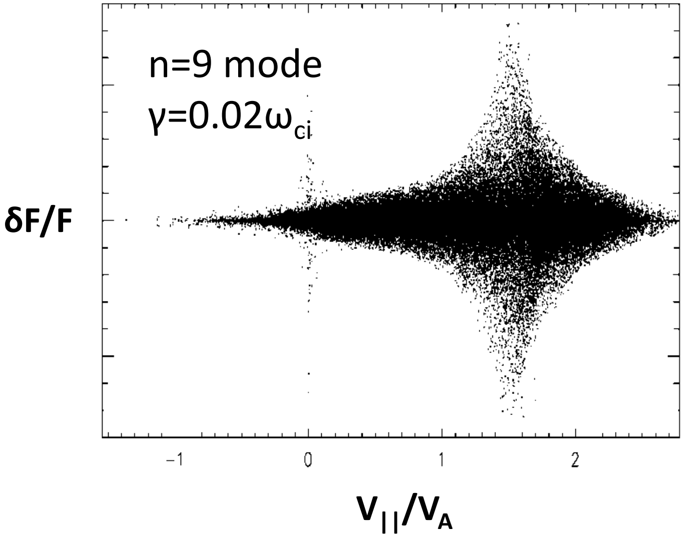


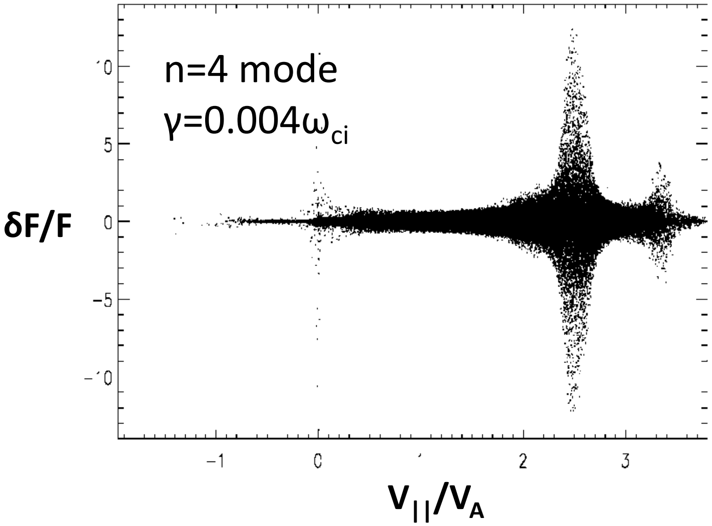
Resonant velocity $V_{||}/V_A\sim1.6$.

For 80keV ions, $V_0/V_A=2.33$, so for resonant ions: $V_{||}/V_0\sim0.7$.

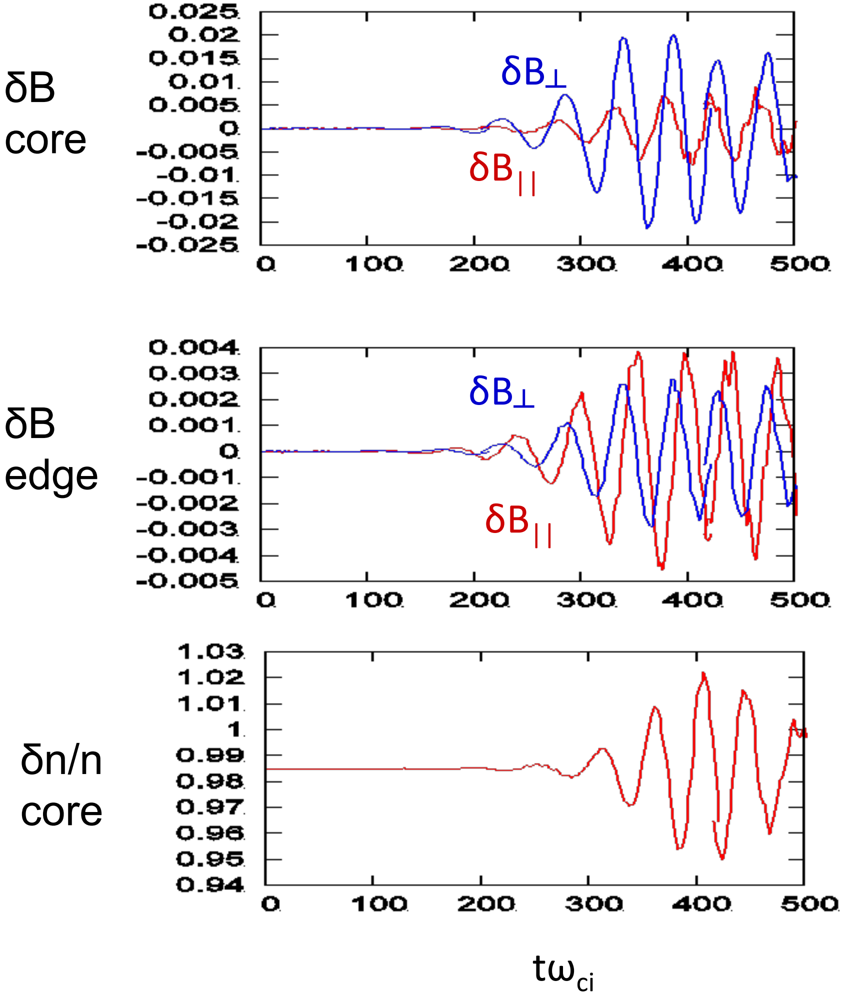
For strongly unstable modes (ie with $\gamma>0.01\omega_{ci}$) broad resonances are observed in phase-space.

Weakly unstable modes show multiple narrow resonances.





Nonlinear simulations



Time evolution of perturbed magnetic field and density from nonlinear simulations for n=9.

Amplitude modulation at the edge and in the core indicates presence of several unstable modes for n=9.

Density perturbation amplitude δn/n~1% is comparable with experimental data [Fredrickson, 2010].

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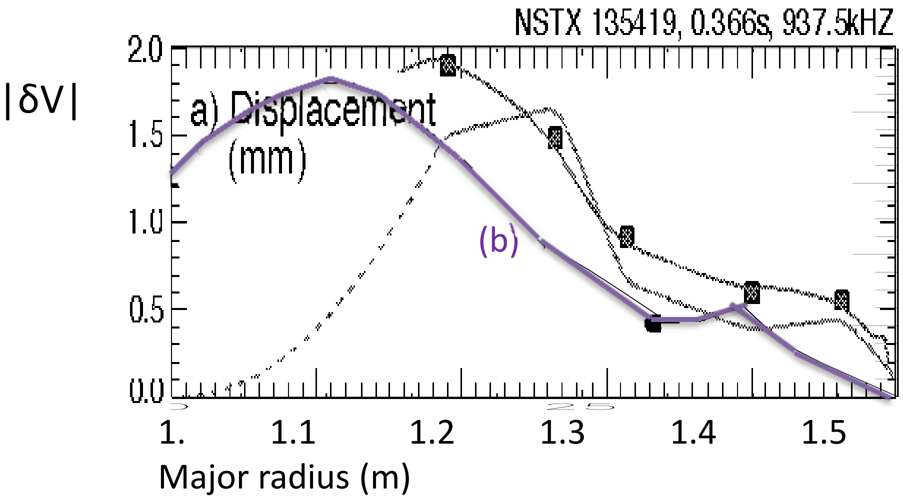
Mode structure: experimental vs numerical profile

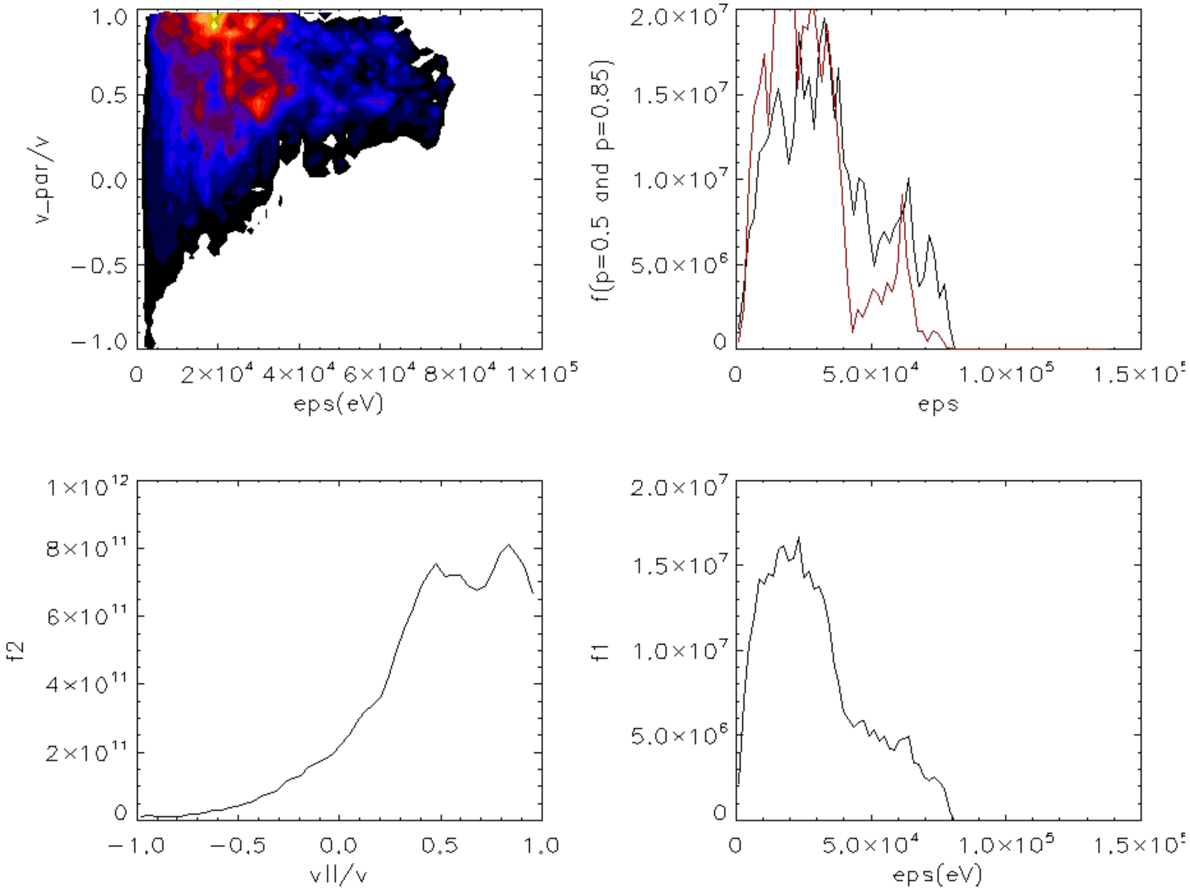
NSTX #135419



a) Mode amplitude profile - displacement
[E. Fredrickson et al, 2009].

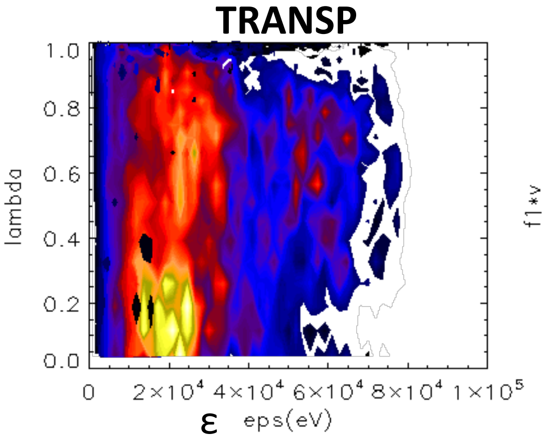
b) Mode structure from HYM simulations -
velocity profile (thin solid line) for n=9.

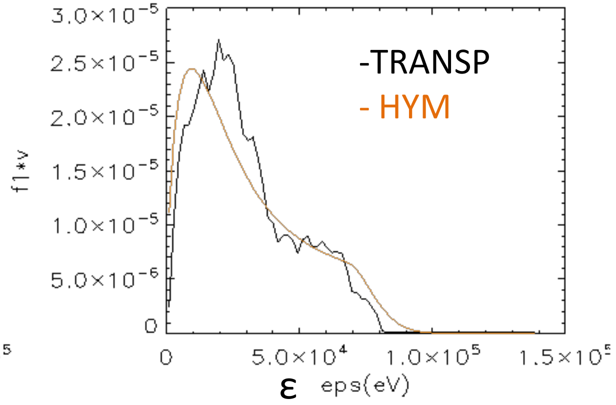
NBI distribution for NSTX shot #130705 (TRANSP)

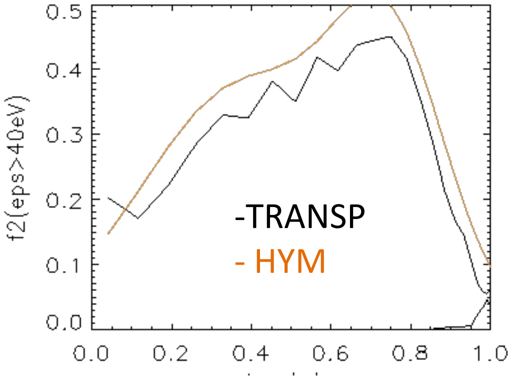


Improved fit for NBI distribution function (vs TRANSP)

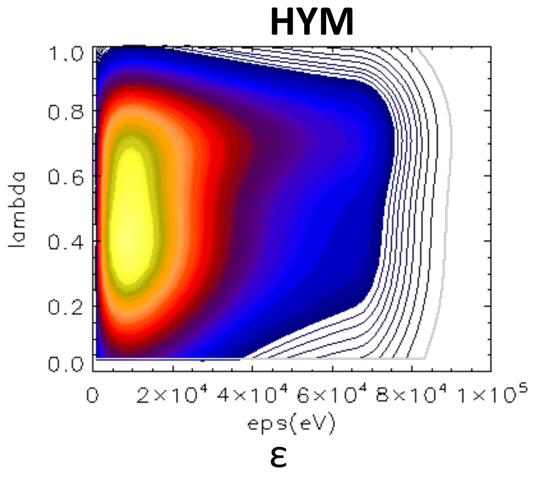
$\lambda = \mu B_0/\varepsilon$
$\approx 1- (V_{||}/V)^2$







$\lambda=\mu B_0/\varepsilon \approx 1- (V_{||}/V)^2$



New code has been written to match fast ion distribution function: two sets of particles with $\lambda_0=0.8$, $\Delta\lambda=0.2$ and $\lambda_0=0.4$, $\Delta\lambda=0.25$, where $f(\lambda) \sim \exp[-(\lambda-\lambda_0)^2/\Delta\lambda^2]$ is assumed.

Conclusions

- Coupling between thermal (MHD) plasma with $p=p(\psi)$ and energetic ions has been modified to include Ohkawa current.
- Unstable mode numbers and growth rates in HYM simulations compare well with experimental results for NSTX shot#135419 [E. Fredrickson et al].
- Magnetic mode structure for GAE in NSTX shows significant compressional component at the edge – good agreement with experimental profile.
- Multiple fast ion resonances are seen for each mode. Stronger instabilities result in broad resonance region – possible overlap between different modes.
- Simulations show nonlinear saturation of GAEs due to particle trapping. Saturation amplitudes are comparable with the observations.

- Drift-kinetic electron model is being implemented in the HYM code – can be used to study the effects of GAE modes on electron transport.