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Numerical simulations of Global Alfven Eigenmode (GAE) stabilization in NSTX-U

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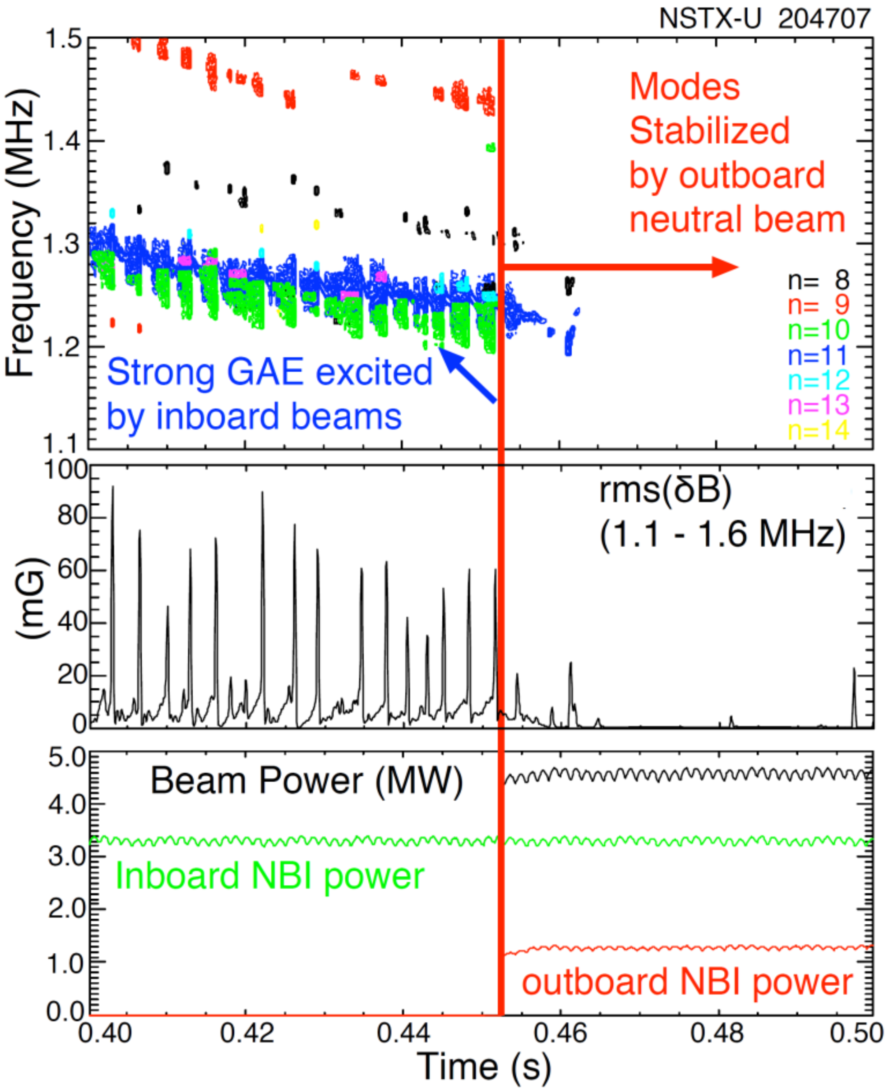
NSTX-U off-axis neutral beam suppresses Global Alfven Eigenmodes (GAEs) [E. Fredrickson, PRL 2017]



- Counter-propagating GAEs are frequently observed in the sub-cyclotron frequency range of $0.1f_{ci}$ up to $0.5f_{ci}$, in NSTX and NSTX-U.
- Driven by cyclotron resonance with beam ions.
- New neutral beam sources -> ability to control the fast ion distribution.
- Off-axis neutral beams inject fast ions onto trajectories largely parallel to the magnetic field, with pitch $0.8<V_{||}/V<1$.
- Reliable suppression of the counter-propagating GAE when an additional 1.3MW is injected using the outboard beam.
- GAE stabilization has been well documented for many shots.

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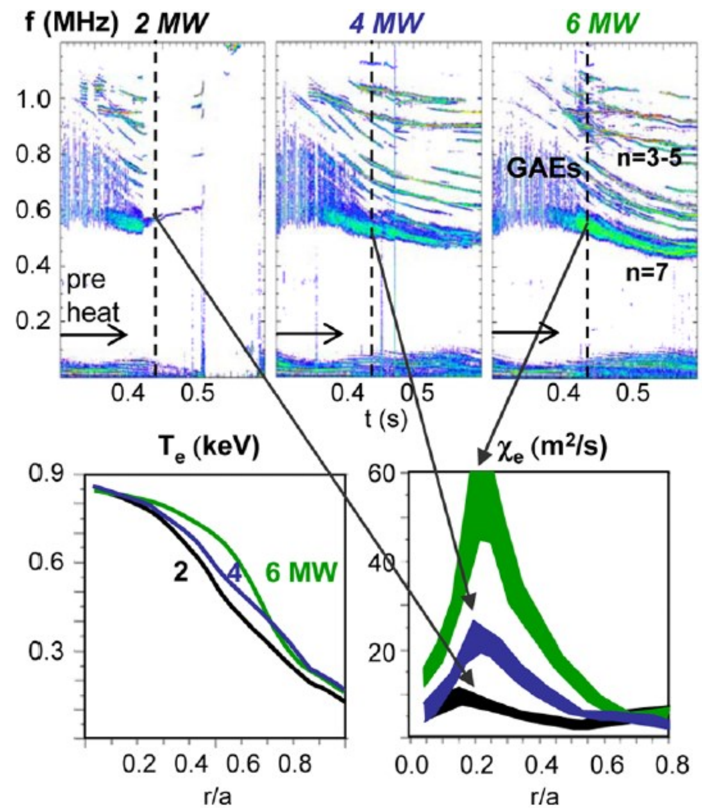
Correlation between strong GAE/CAE activity and flattening of the electron temperature profile has been observed in NSTX [Stutman, PRL 2009]

- Intense GAE/CAE activity (0.5-1.1MHz).
- Flattening of T_e profile with
  - increased beam power;
  - beam energy scanned between 60 and 90 keV [Stutman, PRL 2009].
- Was attributed to
  - enhanced electron transport due to orbit stochasticity in the presence of multiple GAEs [Gorelenkov, NF 2010].
  - energy channeling due to CAE coupling to KAW [Belova, PRL 2015].
- Anomalously low T_e potentially can have significant implications for future fusion devices, especially low aspect ratio tokamaks.



Correlation between GAE activity, T_e flattening, and central electron heat diffusivity χ_e in NSTX H modes with 2, 4, and 6MW neutral beam.

HYM – HYbrid and MHD code

Applications

- NSTX
  - Sub-cyclotron frequency Alfven eigenmodes (GAE and CAE)
- ICC Theory and Modeling
  - Hybrid simulations of spheromak merging
  - FRC: Effects of beam ions on stability
    - Rotation control
    - n=2 rotational and n=1 wobble modes

Code description

- 3-D nonlinear.
- Physical models:
  - Resistive MHD & Hall-MHD
  - Hybrid (fluid electrons, particle ions)
  - **MHD/particle (one-fluid thermal plasma, + energetic particle ions)**
  - Drift-kinetic particle electrons
- Full-orbit kinetic ions.
- For particles: delta-f / full-f numerical scheme.
- Parallel (3D domain decomposition, MPI)

Self-consistent MHD + fast ions coupling scheme

Background 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 – delta-F scheme:

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

$w=\delta F/F$ - particle weight

$$\frac{dw}{dt}=-(1-w)\frac{d(\ln F_0)}{dt}$$

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

ρ, **V** and p are thermal plasma density, velocity and pressure, n_b and $\mathbf{j}_b$ are beam ion density and current, and $n_b << n_e$ – is assumed.

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Self-consistent anisotropic equilibrium including the NBI ions

Grad-Shafranov equation for two-component plasma:

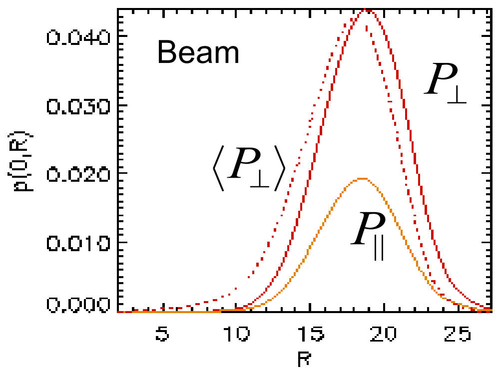
MHD plasma (thermal) and fast ions [Belova et al, Phys. Plasmas 2003].

$$\frac{\partial^2\psi}{\partial z^2}+R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial\psi}{\partial R}\right)=-R^2p'-HH'\underbrace{-GH'+RJ_{b\phi}}_{\text{Beam effects}}$$

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

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

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



Modifications of equilibrium due to beam ions:

- more peaked current profile,
- anisotropic pressure,
- increase in Shafranov shift

might have indirect effect on stability.

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Fast ions – delta-f scheme: $F_0=F_0(\varepsilon,\mu,p_\varphi)$

Equilibrium distribution function $F_0 = F_1(v)\, F_2(\lambda)\, F_3(p_\varphi, v)$

$$F_1(v) = \frac{1}{v^3 + v_*^3}, \text{ for } v < v_0$$

$$F_2(\lambda) = \exp(-(\lambda - \lambda_0)^2 / \Delta\lambda^2)$$

$$F_3(p_\phi, v) = \frac{(p_\phi - p_0)^\beta}{(R_0 v - \psi_0 - p_0)^\beta}, \text{ for } p_\phi > p_0$$

where $v_0 = 2\text{-}5 v_A$, $v_* = v_0/2$, $\lambda = \mu B_0/\varepsilon$ – pitch angle parameter, $\lambda_0 = 0.5\text{-}0.7$, and $\mu = \mu_0 + \mu_1$ includes first-order corrections [Littlejohn'81]:

$$\mu = \frac{(\mathbf{v}_\perp - \mathbf{v_d})^2}{2B} - \frac{\mu_0 v_\|}{2\mathrm{B}}[\hat{b}\cdot\nabla\times\hat{b} - 2(\hat{a}\cdot\nabla\hat{b})\cdot\hat{c}]$$

$\mathbf{v}_d$ is magnetic gradient and curvature drift velocity, $\hat{c} = \mathbf{v}_\perp / v_\perp$, $\hat{a} = \hat{b}\times\hat{c}$.

Parameters are chosen to match TRANSP beam profiles.

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HYM simulations reproduce frequency range of unstable GAE and CAE modes observed in NSTX

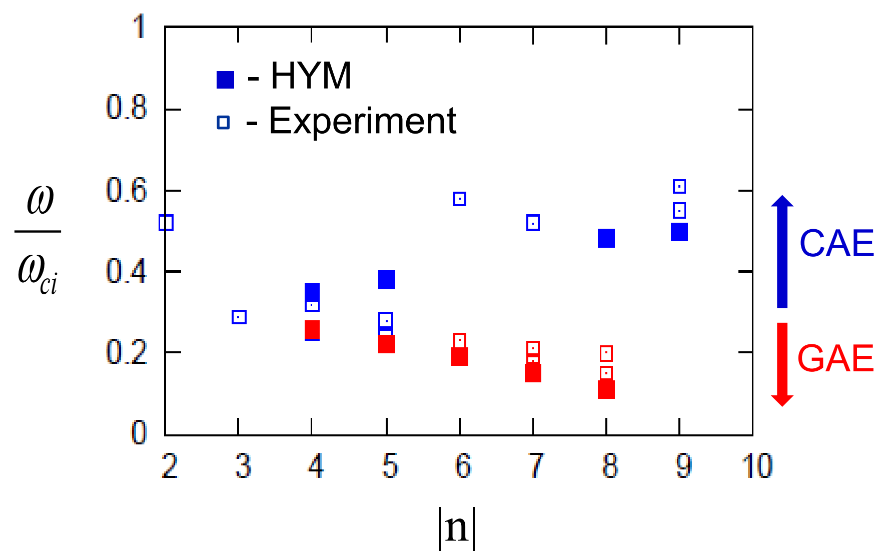
Experimental analysis:

Detailed measurements of GAE and CAE amplitudes and mode structure for H-mode plasma in NSTX shot 141398 [N. Crocker, NF 2013].

- **CAEs**: f>600 kHz, and |n|≤5.
- **GAEs**: f<600 kHz, and |n|~6-8.
- Co- and counter-rotating CAEs with f~1.2-1.8 MHz, and n=6-14 also observed in the same shot [E. Fredrickson, PoP 2013].

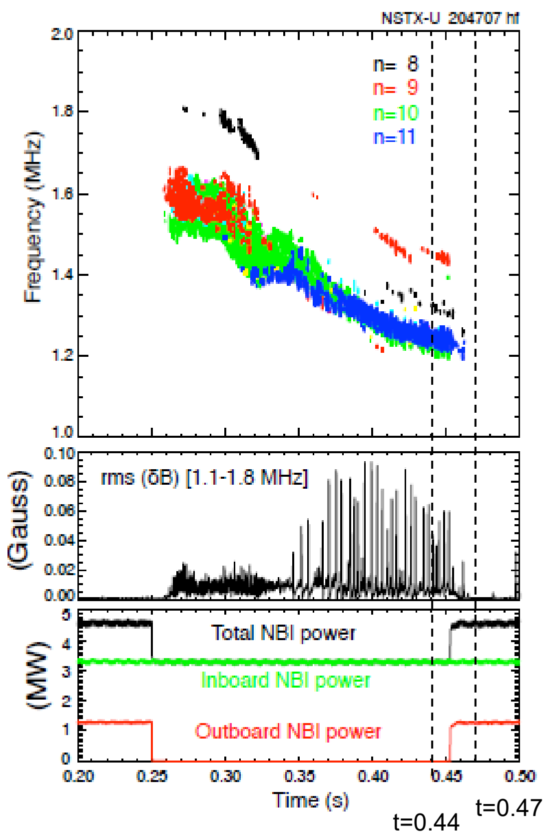
HYM simulations:

- For n=5-7 most unstable are counter-rotating GAEs, with f= 380-550 kHz.
- For n=4 and n=8, 9 most unstable are co-rotating CAEs with f= 870-1200 kHz.



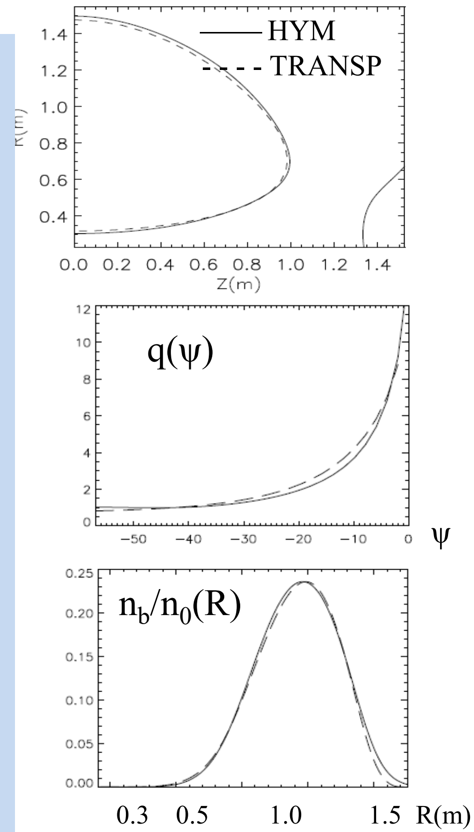
Frequency versus toroidal mode number for unstable GAEs (red) and CAEs (blue), from HYM simulations and experiment, f_{ci}=2.5MHz.

Simulations have been performed to study the excitation and stabilization of GAEs in the NSTX-U



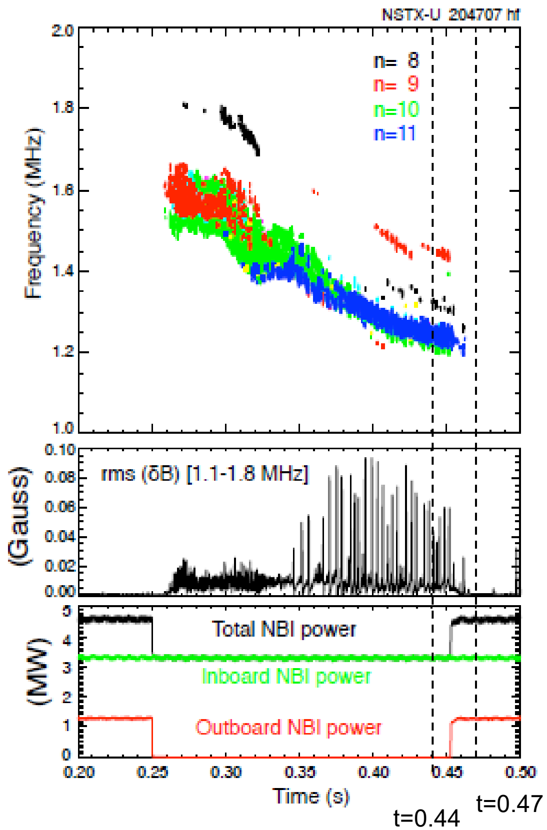
(a) Spectrogram on magnetic fluctuations (n=8-11 counter-GAEs).
(b) Rms magnetic fluctuations;
(c) Injected beam power.

- Simulations using the HYM code have been performed for NSTX-U shot #204707 right before (t=0.44s) and shortly after (t=0.47s) the additional off-axis beam injection.
- Plasma and beam profiles have been chosen to match TRANSP profiles for t=0.44s and t=0.47s.
- The beam ion distribution function matches TRANSP data, with pitch distribution in the form $F_b \sim \exp[-(\lambda-\lambda_0(\varepsilon))^2/\Delta\lambda(\varepsilon)^2]$.



Plasma shape, q- and n_b profiles for NSTX-U shot 204707 t=0.44 from TRANSP and HYM GS solver + FREE_FIX.

HYM reproduces experimentally observed unstable GAEs



(a) Spectrogram on magnetic fluctuations (n=8-11 counter-GAEs).
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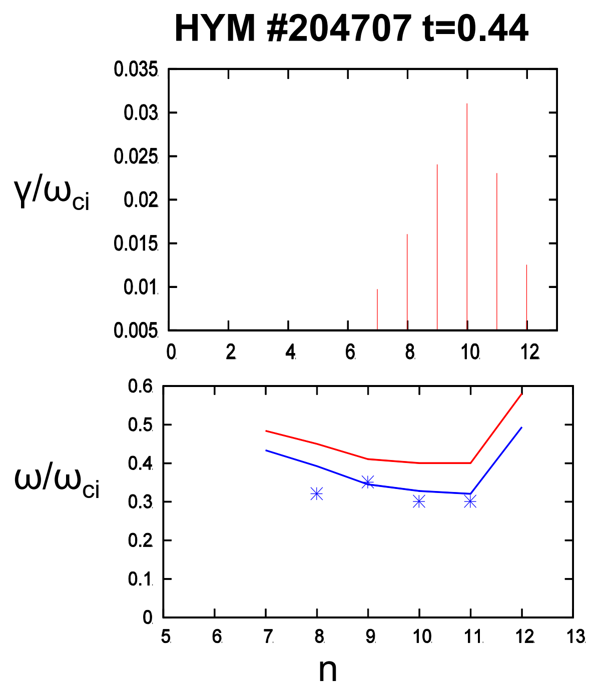
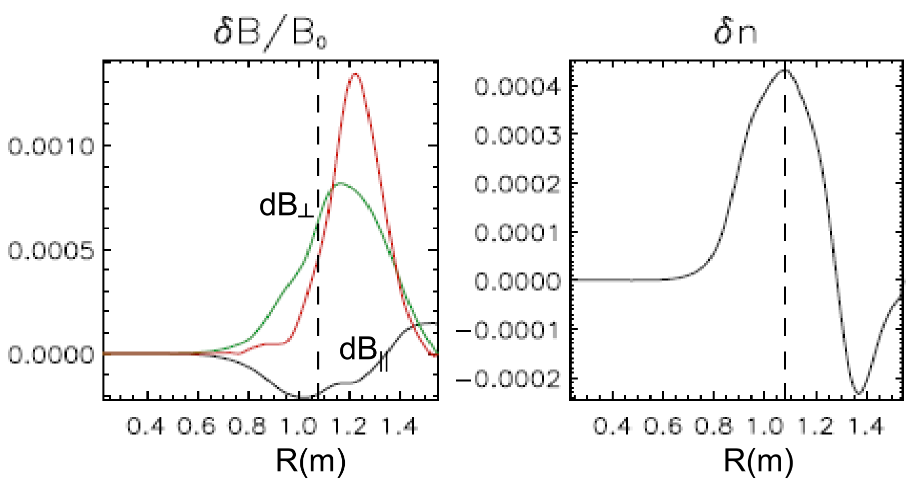


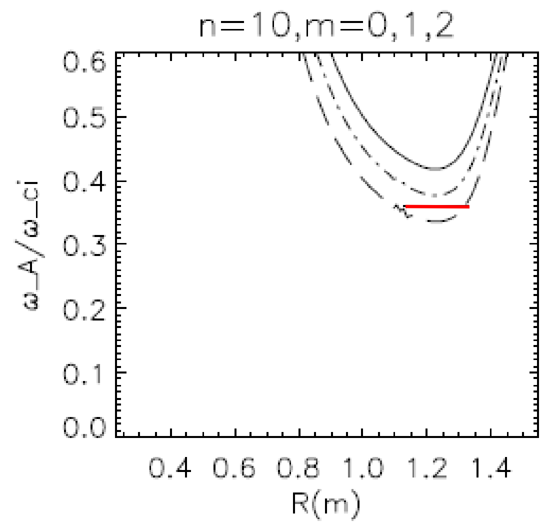
(a) Growth rates and (b) frequencies of unstable counter-GAEs from HYM simulations for t=0.44s. Blue line is Doppler-shift corrected frequencies, points – experimental values.

- Simulations reproduce most unstable toroidal mode numbers and GAEs frequencies.
- HYM overestimates growth rates compared experimental analysis
- Growth rates are sensitive to distribution function parameters – resonance particles are in 'tail' of distribution.

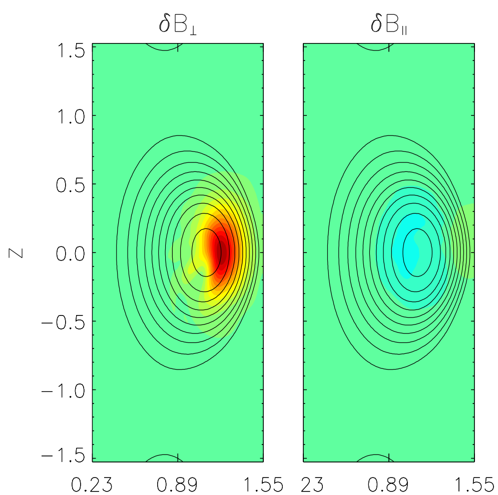
NSTX-U simulations: n=10 counter-GAE (t=0.44s)



Radial profile of **δB** and δn for n=10 counter-GAE.



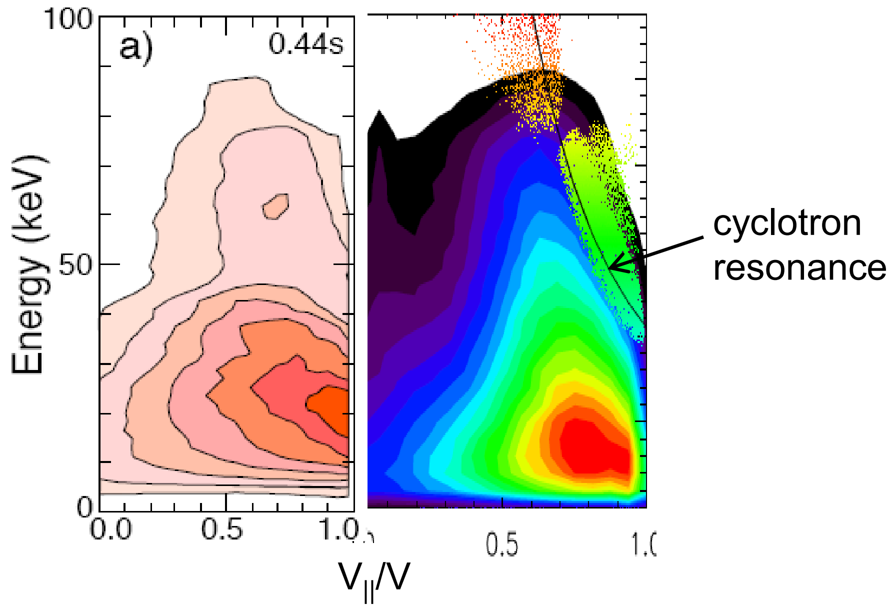
Radial profile of ω_A/ω_{ci} for n=10, m=0-2; location of GAE.



- Unstable modes are counter-rotating and have shear Alfven polarization.
- Located near min of ω_A.

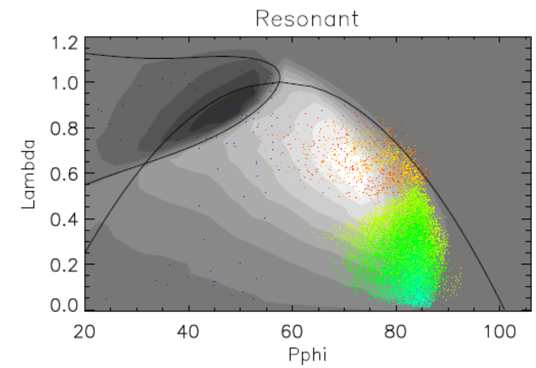
Improved F_{beam} fit allows more accurate description

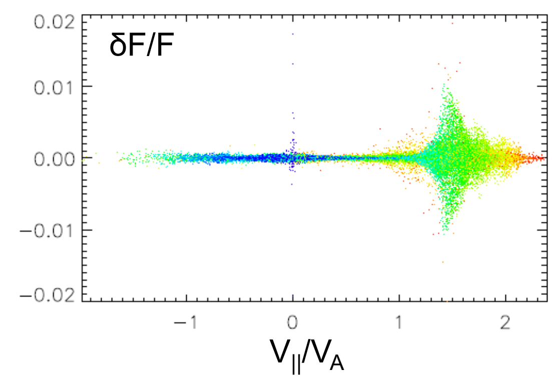
$$F_{beam} \sim \exp(-(\lambda-\lambda_0(v))^2/\Delta\lambda(v)^2)$$



(a) TRANSP fast-ion distribution before the outboard beam injection t=0.44. Exp. estimated γ_{dr}~0.5%ω_{ci} for n=11 GAE;

(b) HYM fast-ion distribution from n=-10 GAE simulations; dots show resonant particles. Improved F_{beam} reduces growth rate γ~1.5%ω_{ci}.

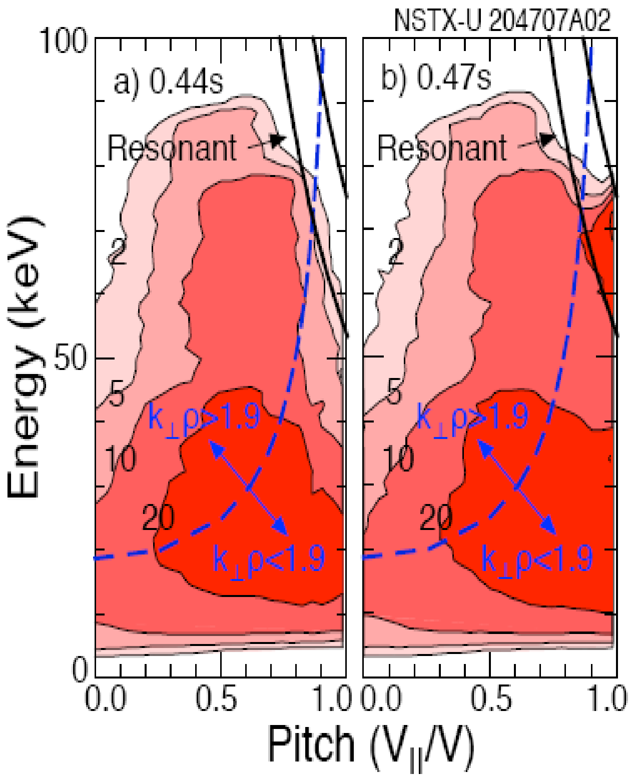




(a) Location of resonant particles in phase space: $\lambda=\mu B_0/\varepsilon$ vs p_φ.

(b) Particle weight w ~ δF/F vs orbit-averaged parallel velocity. Particle color corresponds to different energies: from E=0 (purple) to E=90keV (red).

Off-axis beam injection strongly suppresses all unstable GAEs



TRANSP fast-ion distribution before and after the outboard beam injection. Fast ions with pitch $v_{||}/v{\sim}1$ are responsible for GAE suppression.
Analytical instability condition: $2 < k_\perp\rho_b < 4$ [Gorelenkov,2003].

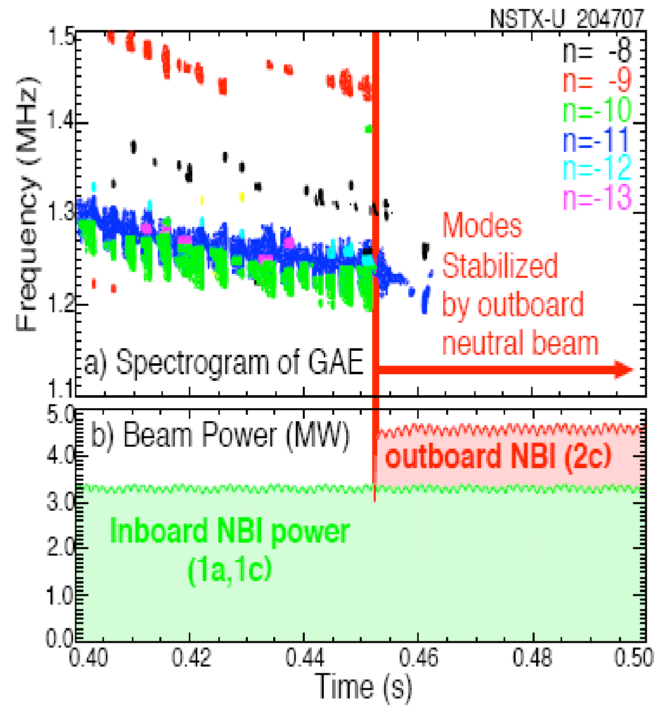
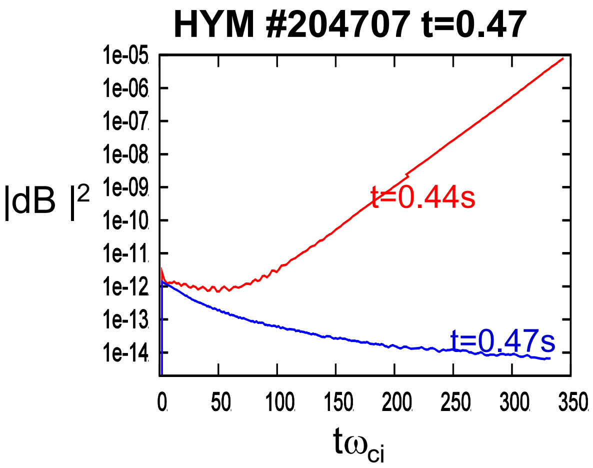


Fig. 2. a) color-coded spectrogram showing ctr-propagating GAE activity. Dominant modes are n=-10 (green) and n=-11 (blue). b) green curve is inboard beam power, red curve is off-axis beam power (source 2c).

HYM simulations reproduce experimental finding: off-axis neutral beam injection reliably and strongly suppresses unstable GAEs

- The beam ion distribution function with pitch distribution in the form $F_b \sim \exp[-(\lambda-\lambda_0(\varepsilon))^2/\Delta\lambda(\varepsilon)^2]$.
- Additional off-axis beam injection modeled by adding beam ions with distribution $F_{add} \sim \exp[-\lambda^2/\Delta\lambda_a(\varepsilon)^2]$, i.e. with $\lambda_0=0$, $\Delta\lambda_a<\Delta\lambda$ and about 1/3 of the total beam ion inventory.
- HYM shows complete stabilization of n= 7-12 counter-GAEs by additional off-axis beam injection.



Time evolution of magnetic energy of n=10 GAE from HYM simulations for t=0.44s (red), and t=0.47s (blue).

Summary and Future Work

- HYM simulations show range of toroidal mode numbers, and frequencies of unstable GAEs that match the experimentally observed GAEs in NSTX-U.
- Growth rate of GAE is sensitive to details of beam ion distribution.
- Simulations reproduce experimental finding, namely it is shown that off-axis neutral beam injection reliably and strongly suppresses all unstable GAEs.
- A robust physical mechanism for stabilizing GAEs - threshold for stabilization for additional beam is less than 25% of total beam power.

Future work:

- Understanding instability conditions for excitation of counter-GAEs – comparison with analytical condition.
- Bulk plasma rotation and Hall term can have effect on GAE stability and mode structure.
- Comparison with experimental results including mode structure, saturation amplitudes and etc for several shots.