27th IAEA FUSION ENERGY CONFERENCE Gandhinagar (Ahmedabad) INDIA, October 2018

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

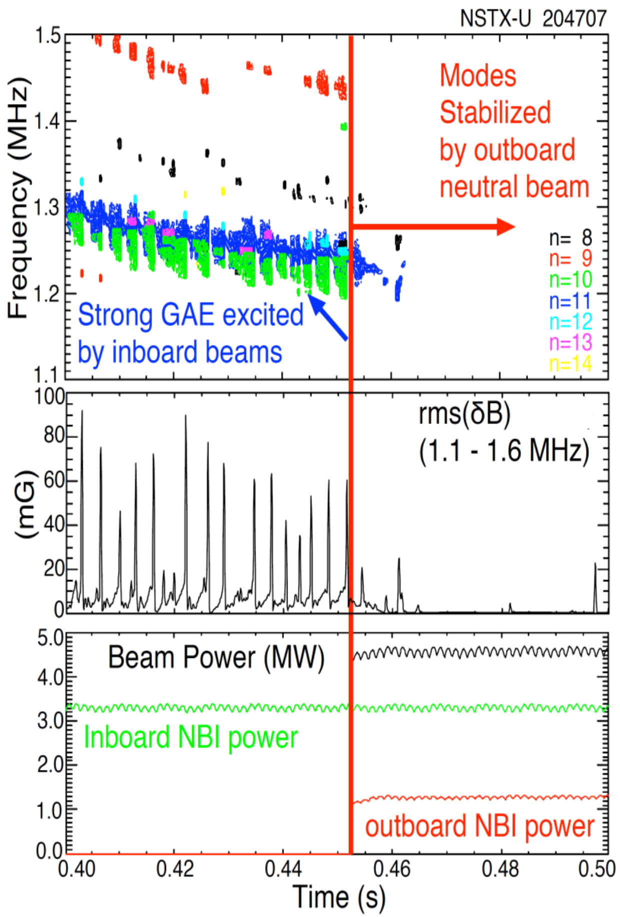
E. V. Belova[1], E. D. Fredrickson[1], N. A. Crocker[2], and the NSTX-U team

1) Princeton Plasma Physics Laboratory, Princeton NJ, USA
2) University of California, Los Angeles, California 90095, USA

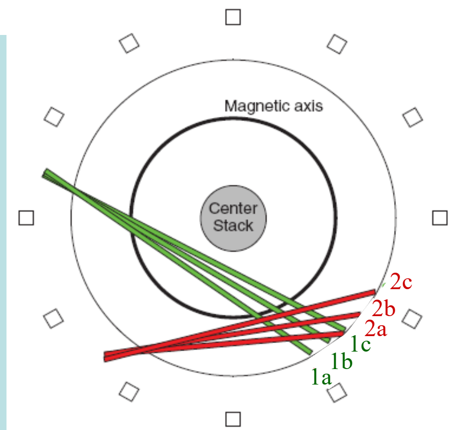
NSTX-U

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

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



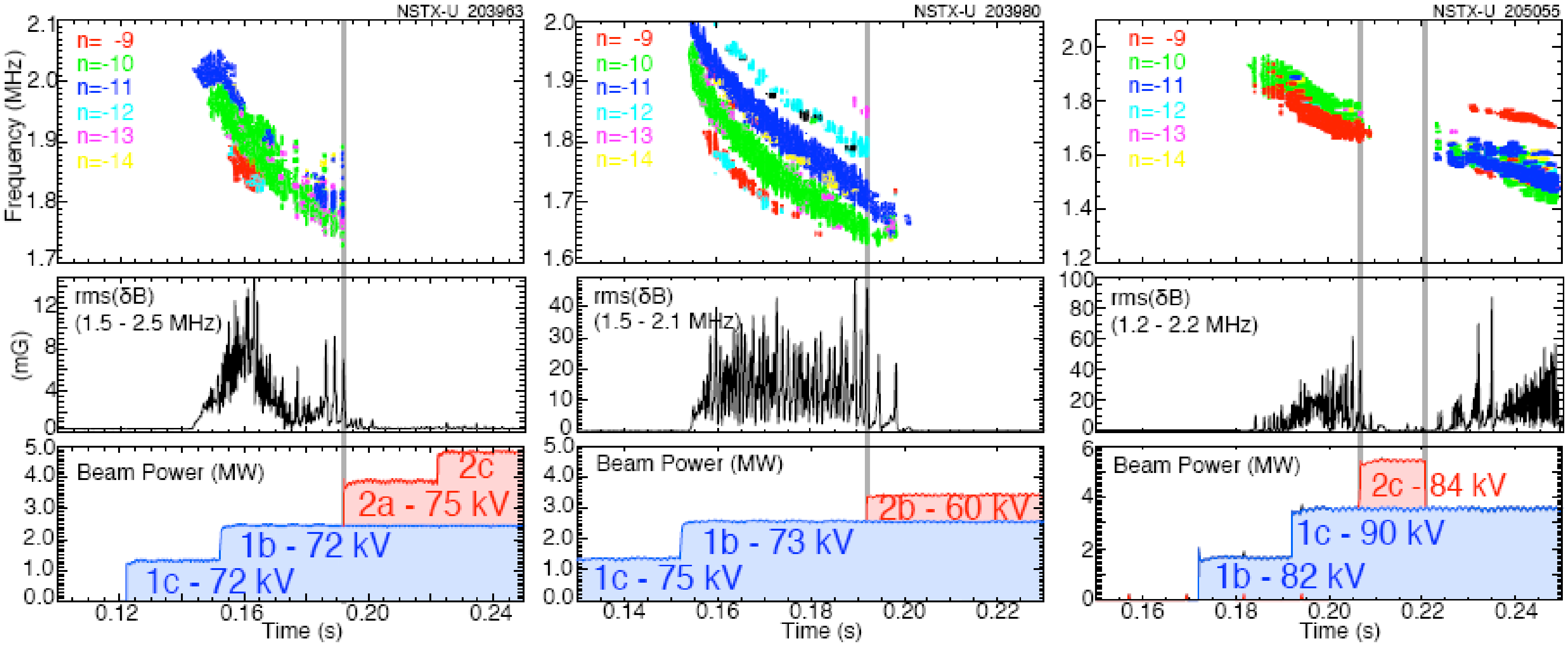
- Counter-propagating GAEs are frequently observed in the sub-cyclotron frequency range of $0.1f_{ci}$ up to $0.5f_{ci}$, in NSTX and NSTX-U.
- Driven by cyclotron resonance with beam ions
- New neutral beam sources — ability to control the fast ion distribution.



Sketch of neutral beam geometry. Original beams in green, labeled 1a, 1b, 1c; new beams for NSTX-U shown in red labeled 2a, 2b and 2c.

- 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 NSTX-U shots



Three examples of GAE being suppressed by the injection of one of the three off-axis beam sources. Figure 1(c) also shows that the GAE can reappear when the 2c power is turned off.

The measured GAE suppression time ~ few ms is much smaller than slowing-down time (~50ms), suggesting that it takes relatively few high-pitch fast ions to suppress the GAE.

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.

Self-consistent anisotropic equilibrium including the NBI ions

Grad-Shafranov equation for two-component plasma:

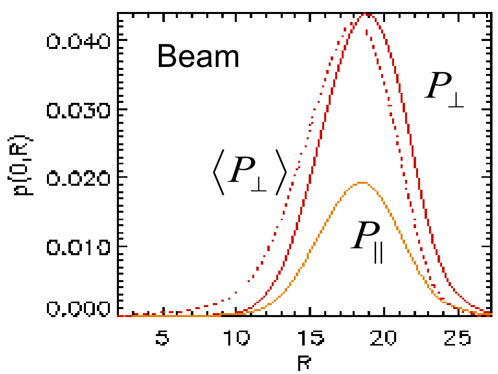
MHD plasma (thermal) and fast ions [Belova et al, Phys. Plasmas 2003].

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

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

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

$\mathbf{J}_{bp} = \nabla G\times\nabla\phi$, $G-$ 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.

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

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

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

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

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

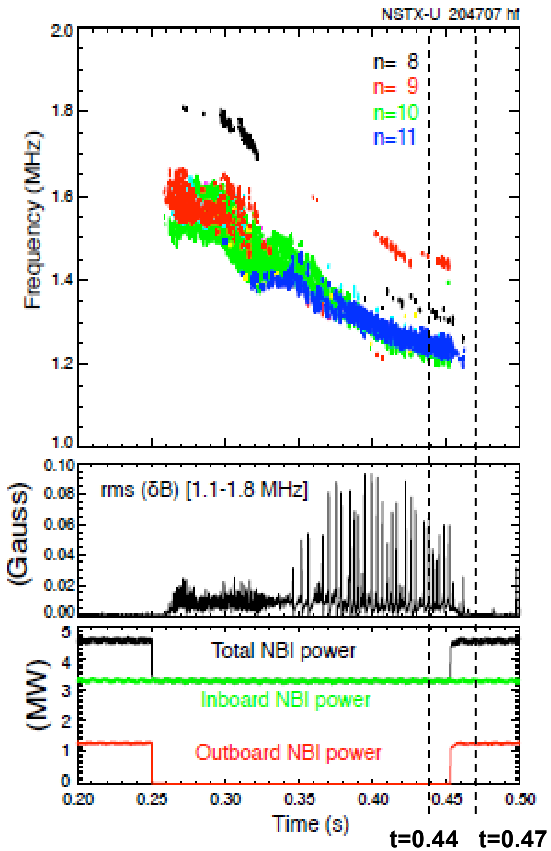
where $v_0 = 2\text{-}5v_A$, $v_* = v_0/2$, $\lambda = \mu B_0/\varepsilon$ – pitch angle parameter, $\lambda_0 = 0.5\text{-}0.7$ (typical of on-axis beam), and $\mu = \mu_0 + \mu_1$ includes first-order corrections [Littlejohn'81]:

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

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

Parameters are chosen to match TRANSP beam profiles.

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

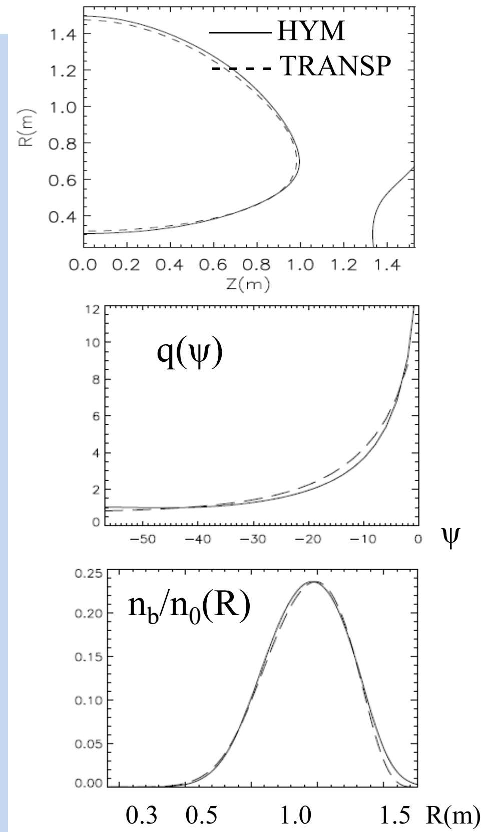


(a) Spectrogram on magnetic fluctuations (n=8-11 counter-GAEs).
(b) Rms magnetic fluctuations;
(c) Injected beam power.

- 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

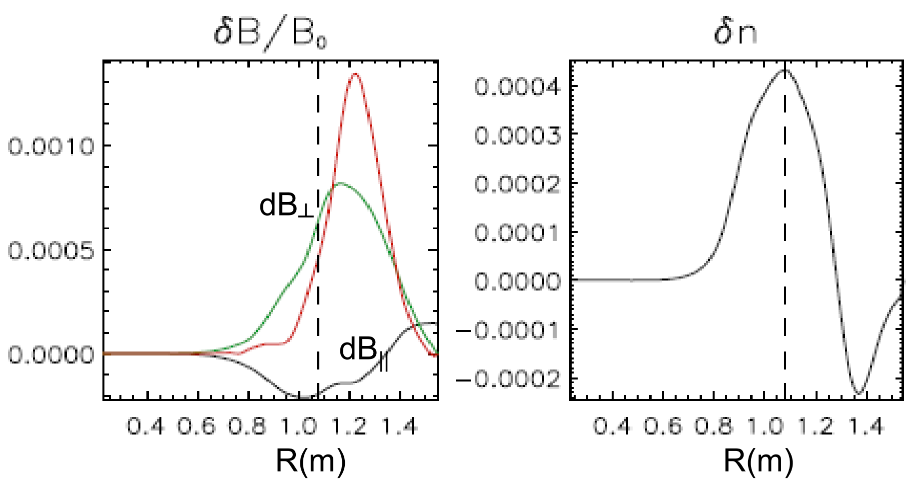
$$F_b \sim \exp[-(\lambda-\lambda_0(\varepsilon))^2/\Delta\lambda(\varepsilon)^2] -$$

improved fit includes energy dependence of pitch distribution.

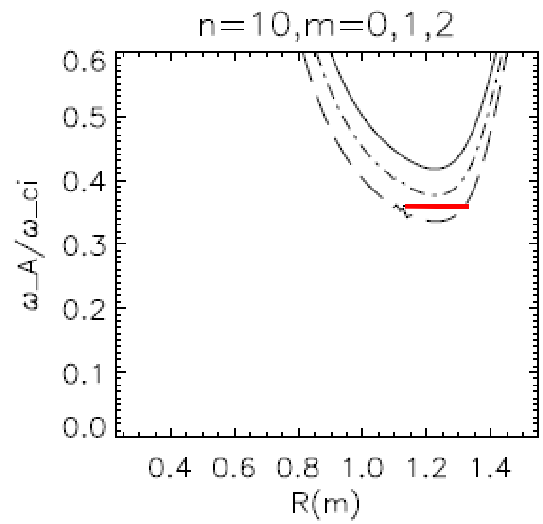


Plasma shape, q- and n_b profiles for NSTX-U shot 204707 t=0.44 from TRANSP and HYM GS solver + FREE_FIX.

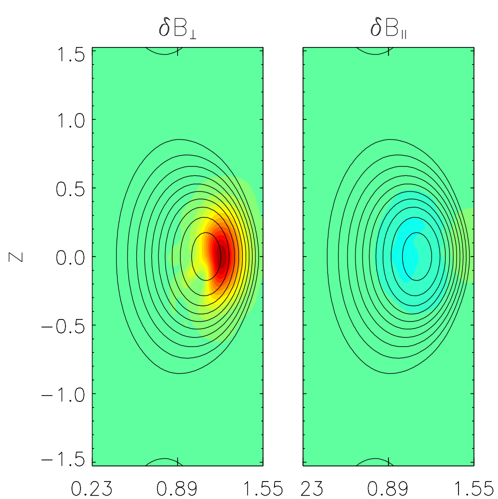
NSTX-U linear simulations: n=-10 counter-GAE (t=0.44s)



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

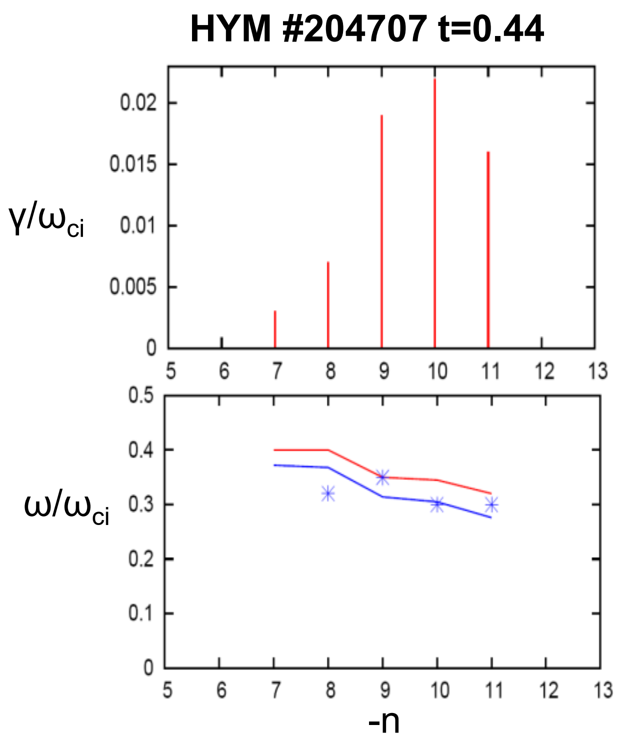


Radial profile of ω_A/ω_{ci} for n=-10, m=0-2; location of GAE.



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

HYM reproduces experimentally observed unstable GAEs

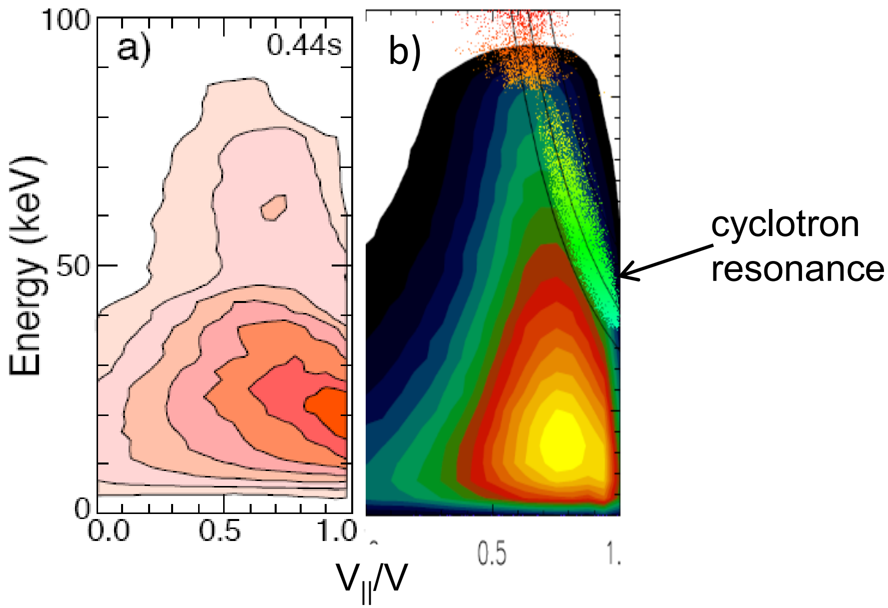


(a) Growth rates and (b) frequencies of unstable counter-GAEs from HYM simulations for t=0.44s. Blue line is Doppler-shift corrected frequencies, points – experimental values.

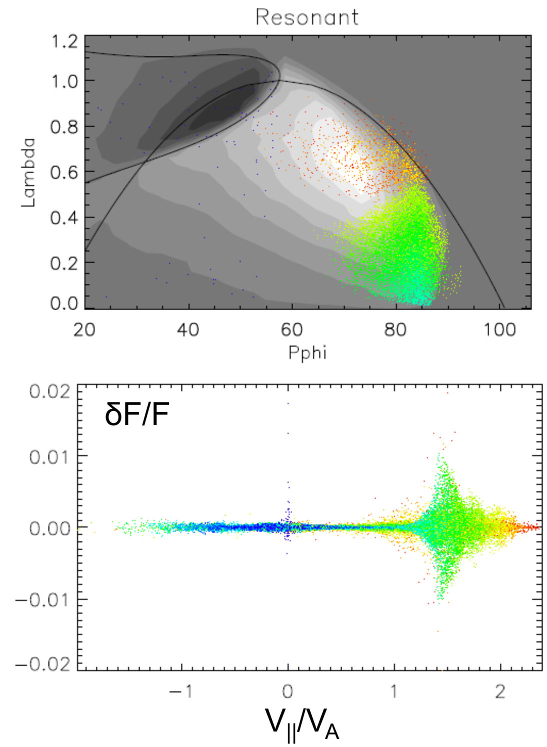
- Simulations reproduce most unstable toroidal mode numbers and GAEs frequencies.
- HYM overestimates growth rates compared experimental analysis by 2-3 times.
- Experimental estimates [Fredrickson, NF 2018]:
  - n=-10 γ/ω_{ci}=0.84%
  - n=-11 γ/ω_{ci}=0.6%
- Growth rates are sensitive to distribution function parameters – resonance particles are in 'tail' of distribution.

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.
(b) HYM fast-ion distribution from n=-11 GAE simulations; dots show resonant particles.

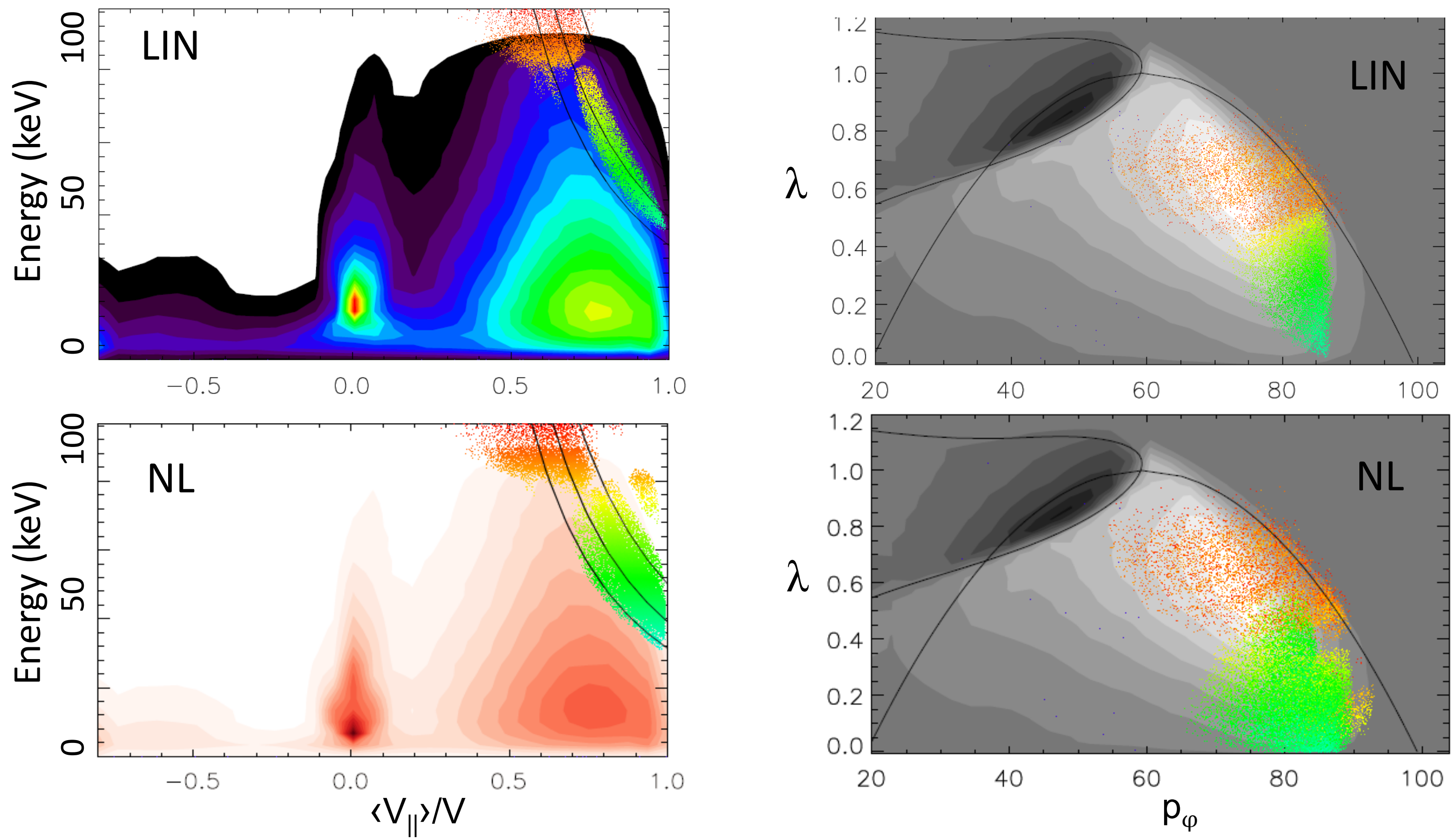


(a) Location of resonant particles in phase space: $\lambda=\mu B_0/\varepsilon$ vs p_φ.
(b) Particle weight $w \sim \delta F/F$ vs orbit-averaged parallel velocity. Particle color corresponds to different energies: from E=0 (purple) to E=90keV (red).

NSTX-U

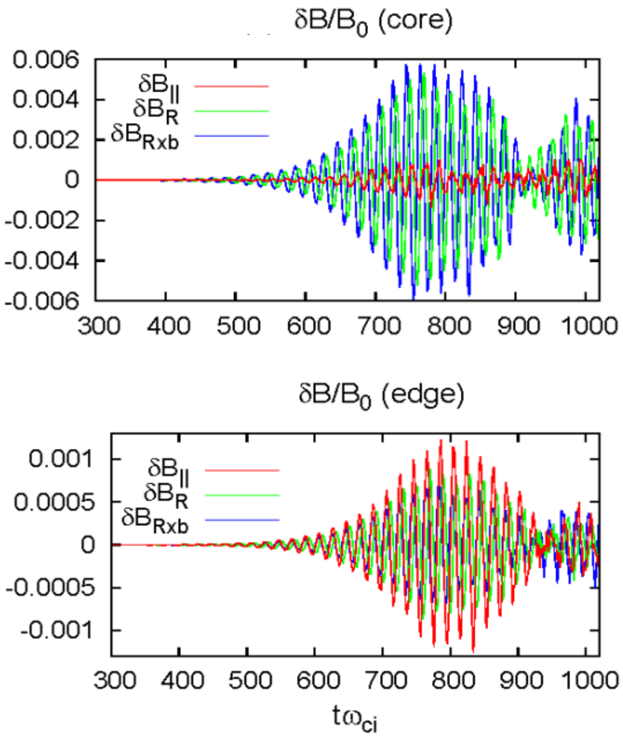
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Resonant region is wider in nonlinear phase



Location of resonant particles in phase space; from linearized and nonlinear simulations of n=-11 GAE. Particle color corresponds to different energies: from E=0 (purple) to E=90keV (red); $\langle V_{||} \rangle$ - orbit averaged velocity.

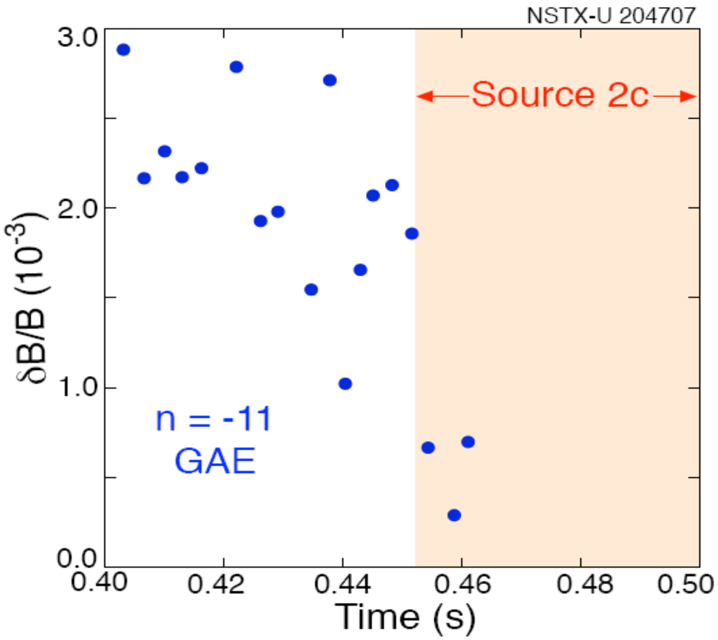
Nonlinear simulations: n=-11 counter-GAE (t=0.44s)



Time evolution of perturbed magnetic field components from nonlinear simulations for n=-11 GAE.

- Nonlinear simulations show peak saturation amplitudes of $\delta B/B_0 \sim 5\times10^{-3}$ at R~1.2m close to the minimum of the Alfvén continuum, and $\delta B/B_0 \sim 10^{-3}$ near the edge at the midplane.
- Unstable modes have shear Alfven polarization in the core, and mixed polarization at the edge.

Experimental amplitudes estimates are comparable to nonlinear simulation results



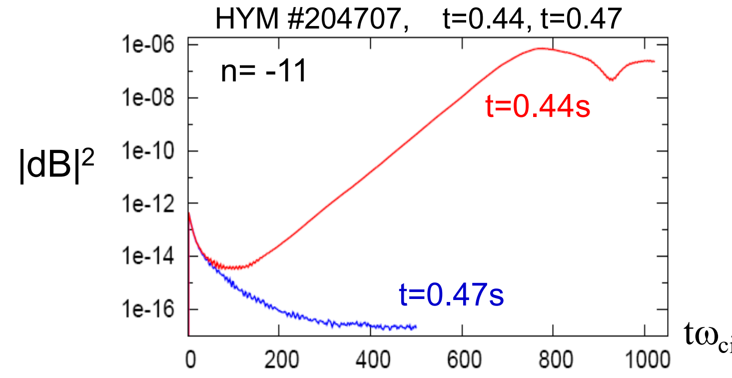
Time evolution of peak amplitude of n=-11 GAE in NSTX-U shot 204707, based on reflectometer reconstructions [E. Fredrickson].

- Approximate peak amplitudes averaged over the time window. A correction factor (the ratio between peak and average amplitude) varied between 1.2 and 2.7.
- Experimental estimates of the peak mode amplitudes are $\delta B/B_0 \approx 2.7 \cdot 10^{-3}$ for the n=-10 and $\delta B/B_0 \approx (1\text{-}2) \cdot 10^{-3}$ for the n=-11 modes at t~0.44s.
- Large uncertainty is in the reflectometer reconstructions which depend on accurate density profile gradient data.

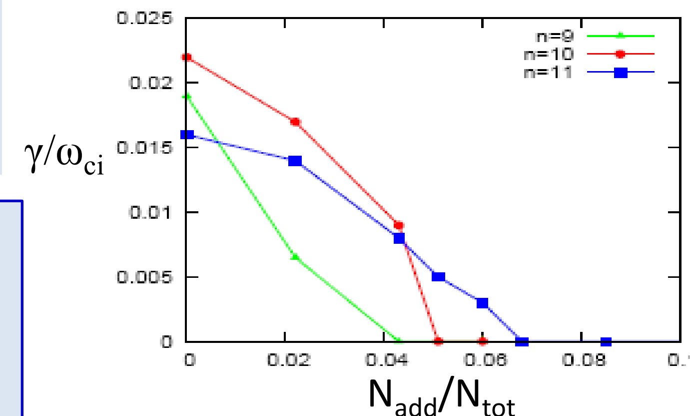
HYM simulations reproduce experimental finding: off-axis neutral beam injection reliably and strongly suppresses unstable GAEs

- Off-axis beam injection has been modelled by adding beam ions with distribution $F_{add} \sim \exp[-\lambda^2/\Delta\lambda\,(\varepsilon)^2]$, and varying density.
- For NSTX-U beam parameters, HYM shows complete linear stabilization of all unstable GAEs.
- In additional simulations, fraction of off-axis beam population of the total fast ion inventory has been varied from 4% to 17%.
- Unstable n=-11 GAE is stabilized when the fraction of the off-axis beam ions is larger than 7%
- Stabilization threshold is lower for lower |n| modes.

Fraction of outboard beam power vs total beam power in NSTX-U was ~24-30%, but the GAEs become suppressed at the point where the fast ion population has increased by 6% (based on the neutron rate increase by 6%) – excellent agreement with simulations.



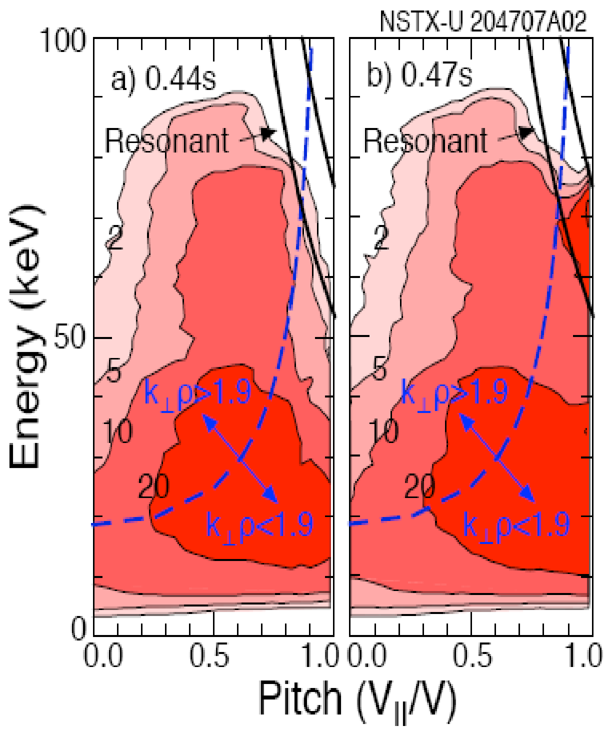
Time evolution of magnetic energy of n=-11 GAE from HYM simulations for t=0.44s (red), and t=0.47s (blue).



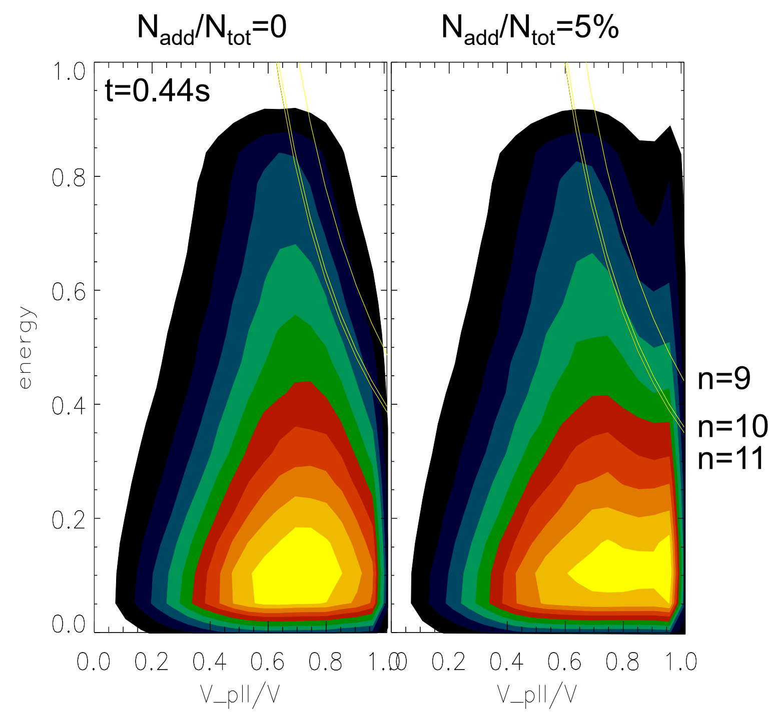
Growth rates of n=-11 (blue), -10 (red), -9 (green) GAEs vs fraction of outboard beam ion population.

GAE stabilization is consistent with analytic predictions

Analytical instability condition: $2 < k_{\perp}\rho_b < 4$ [Gorelenkov,2003] – large pitch particles are stabilizing.



TRANSP fast-ion distribution before and after the outboard beam injection. Fast ions with pitch $v_{||}/v{\sim}1$ are responsible for GAE suppression [Fredrickson,2017].



Fast-ion distribution from HYM simulations before the outboard beam injection and for case with $N_{add}/N_{tot}=5\%$ (n=9,10 are stable). Cyclotron resonance lines are shown for n=9,10,11 GAEs.

Summary

- Simulations confirm robust stabilizing mechanism for beam-driven global Alfvén eigenmodes (GAEs) discovered experimentally in NSTX-U, where new beam sources injecting nearly parallel to magnetic field reliably and strongly suppressed unstable GAEs [E. Fredrickson, PRL 2017].
- GAEs have been linked to flattening of electron temperature profiles and anomalously low central temperature at high beam power in the NSTX.
- Good agreement of simulations with experimental observations:

  - range of toroidal mode numbers, frequencies, and saturation amplitudes of unstable GAEs match the experimentally observed.
- A very effective mechanism for stabilizing GAEs - threshold for stabilization of all modes for extra beam is less than 7% of total beam power – demonstrated both experimentally and numerically.
- Relevant to ITER, and other fusion devices where super-Alfvénic fast ions might be present.