# NUMERICAL SIMULATIONS OF GAE STABILIZATION IN NSTX-U

E.V. BELOVA
Princeton Plasma Physics Laboratory
Princeton NJ, USA
Email: ebelova@pppl.gov

E.D. FREDRICKSON
Princeton Plasma Physics Laboratory
Princeton NJ, USA

N.A. CROCKER
University of California
Los Angeles, California, USA

NSTX-U TEAM
Princeton Plasma Physics Laboratory
Princeton NJ, USA

**Abstract**

Simulations of confinement-limiting Alfvén eigenmodes in the sub-cyclotron frequency range show a robust physical stabilizing mechanism via modest off-axis beam injection, in agreement with experimental observations from National Spherical Torus Experiment (NSTX-U). Experimental results from NSTX-U have demonstrated that neutral beam injection from the new beam sources with large tangency radii deposit beam ions with large pitch, which can very effectively stabilize all unstable Global Alfvén Eigenmodes (GAEs). Beam-driven GAEs have been linked to enhanced electron transport in NSTX, and the ability to control these modes will have significant implications for NSTX-U, ITER, and other fusion devices where super-Alfvénic fast ions might be present. Nonlinear simulations using the HYM code have been performed to study the excitation and stabilization of GAEs in the NSTX-U right before and shortly after the additional off-axis beam injection. The simulations reproduce experimental finding, namely it is shown that off-axis neutral beam injection reliably and strongly suppresses all unstable GAEs. Before additional beam injection, the simulations show unstable counter-rotating GAEs with toroidal mode numbers and frequencies that match the experimentally observed modes. Additional of-axis beam injection has been modelled by adding beam ions with large pitch, and varying density. The complete stabilization occurs at less than 10% of the total beam ion inventory.

## 1. INTRODUCTION

Three dimensional nonlinear simulations of confinement-limiting Alfvén eigenmodes in the sub-cyclotron frequency range have been performed to study the recently discovered stabilization [1] of these modes in National Spherical Torus Experiment (NSTX-U). Simulations using the HYM code confirm a robust physical stabilizing mechanism via modest off-axis beam injection [1]. Compressional Alfvén eigenmodes and Global Alfvén eigenmodes (GAEs), which are frequently excited during neutral beam injection (NBI), are driven unstable through the Doppler shifted cyclotron resonance with the super Alfvénic NBI ions [2,3]. These modes can be excited in ITER due to super Alfvénic velocities and strong anisotropy of the beam ions. They can also be excited by alpha particles near the outer edge of ITER plasma due to anisotropies in alpha particle distribution. Observations link these modes to flattening of electron temperature profiles and anomalously low central temperature at high beam power in the NSTX [4], therefore, the ability to control them will have significant implications for NSTX-U, ITER, and other fusion devices where super-Alfvénic fast ions might be present. NSTX-U results show that the use of an additional neutral beam with large tangency radii provides an excellent technique to control the counter-propagating GAEs excited for $|n|=8$-$13$ and frequencies up to $0.5\omega_{ci}$. Moreover, the complete stabilization of all unstable GAEs in NSTX-U has been robustly achieved by a relatively small population of resonant high-pitch ions [1].

## 2. BEAM-DRIVEN GLOBAL ALFVÉN EIGENMODES IN NSTX-U

Numerical simulations using the HYM code [5-7] have been performed to study the excitation and stabilization of counter-propagating GAEs in the NSTX-U shot #204707 right before (t=0.44s) and shortly after (t=0.47s) the additional off-axis beam injection (Fig.1a). The HYM code is an initial value 3D nonlinear, global stability code in toroidal geometry, which treats the beam ions using full-orbit, delta-f particle simulations, while the one-fluid resistive MHD model is used to represent the background plasma [6]. The excitation of GAEs has been studied for NSTX-U shot 204707 at t=0.44, where the plasma was heated by 3.2 MW of 87 keV Deuterium beams with

$n_b$=7.7×10$^{18}$ m$^{-3}$, $n_e$= 3.3×10$^{19}$ m$^{-3}$, $B_t$= 0.546 T, $I_p$= 0.61 MA, and beam velocity $v_0$= 2$V_A$.The beam ion distribution function has been chosen to match the TRANSP data for this shot, with pitch distribution in the form $F_b \sim \exp[-(\lambda-\lambda_0(\varepsilon))^2/\Delta\lambda(\varepsilon)^2]$, where $\lambda=\mu B_0/\varepsilon$ is the pitch parameter, and assuming a slowing-down distribution in the beam ion energy, ε [5,6]. The pitch-angle distribution of [6] has been generalized to include $\lambda_0$ and Δλ dependence on energy for improved fit to TRANSP (Fig.2a,b).

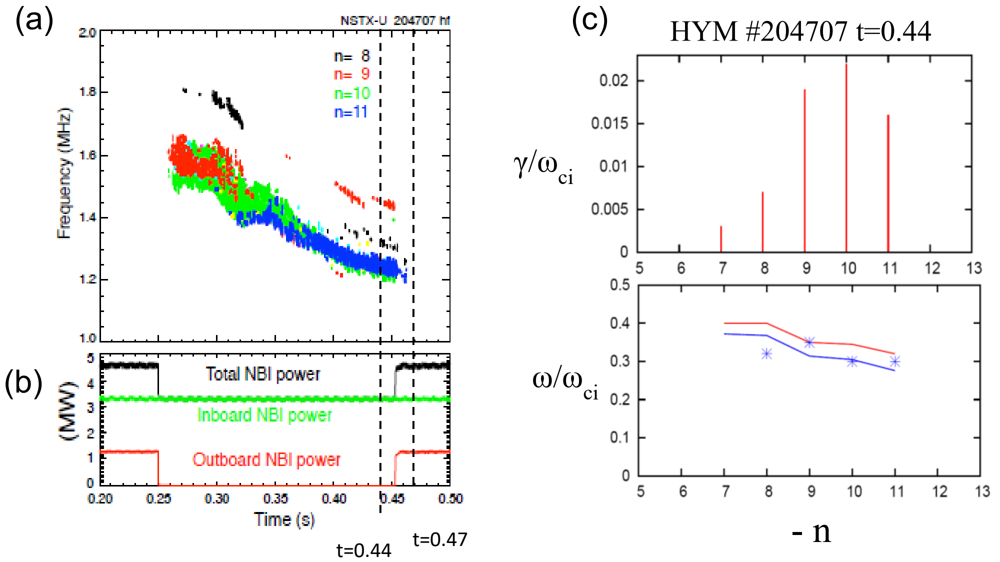


*FIG. 1. (a) Spectrogram on magnetic fluctuations (|n|=8-11 counter-GAEs); (b) Injected beam power; (c) Growth rates and frequencies of unstable counter-GAEs from HYM simulations. Blue line is Doppler-shift corrected frequencies, points – experimental values.*

HYM simulations reproduce the experimental finding, namely, before additional beam injection the simulations show unstable counter-rotating GAEs with toroidal mode numbers n= -11 ÷ -7, and frequencies that match the experimentally observed unstable GAEs (Fig.1c). Figure 1c summarizes the results of a set of linearized simulation runs for different toroidal mode numbers. Numerical simulations show that all unstable modes are counter-rotating GAEs, which have shear Alfvén wave polarization in the core with small $\delta B_\parallel$. All modes in simulations also have small main poloidal mode numbers with m≤3. Most unstable toroidal mode numbers, n= -11 ÷ -9, are consistent with the experiment (Fig 1a). Frequencies for unstable GAEs, $\omega/\omega_{ci}$=0.35–0.4, are calculated in plasma frame (no bulk plasma rotation included in the numerical model), and normalized to the ion cyclotron frequency at the axis $f_{ci}$ = 4.15 MHz. When the bulk plasma toroidal rotation is taken into account via Doppler-shift correction to frequencies, the calculated values (blue line in Fig.1c) match experimental ones (t=0.44s) reasonably close. The calculated growth rates (Fig.2c) for the GAEs with n= -10 and -11 are $\gamma/\omega_{ci}$=2.2% and 1.6% respectively, which is higher than estimated from the experimental data ($\gamma/\omega_{ci}$=0.84% and 0.6%) [8], probably, due to an underestimated damping by the bulk plasma MHD model.

The growth rates are also sensitive to distribution function parameters, especially since the resonant particles are located in the 'tails' of F(λ,ε) distribution, as can be seen in Fig.2b, where the HYM fast-ion distribution function from n= -11 GAE simulations (t=0.44s) is shown. The resonant lines are shown for the main Doppler-shifted cyclotron resonance and side-band (m+/-1) resonances. The colour dots show resonant particles (defined as large-weight particles in delta-f simulations), with particle color corresponding to beam ion different energies: from E=0 (purple) to E=90keV (red). The resonant particles are passing particles, they have a wide range of energies and relatively small pitch angle parameters λ<0.4 (high pitch). Additional analysis of the simulation data shows that the beam ions with energies of about half of the injection energy (~50keV) and pitch of $V_\parallel/V$~0.9 are responsible for the instability drive.

Nonlinear simulations of the $n$ = -11 ÷ -9 GAEs have been performed in order to identify the instability saturation mechanism, find the mode amplitude at the saturation and compare with experimental data. The nonlinear simulation in each case has been performed for a single toroidal harmonic, but includes a full nonlinear beam ion response. In the simulations the instability saturates due to nonlinear particle trapping, and the amplitude evolution in the nonlinear phase (Fig. 2c and 3b) exhibits characteristic oscillations consistent with the particle trapping saturation mechanism. The simulations for n= -11 (Fig.2c) show the peak saturation amplitudes of $\delta B/B_0$~5×10$^{-3}$ at R~1.2m close to the minimum of the Alfvén continuum, and $\delta B/B_0$~10$^{-3}$ near the edge at the midplane. For comparison, experimental estimates of the peak mode amplitudes are $\delta B/B_0 \sim 2.7\cdot 10^{-3}$ for the n= -10 and $\delta B/B_0 \sim 1.8\cdot 10^{-3}$ for the n= -11 modes [8], i.e. fairly close to the simulation results.

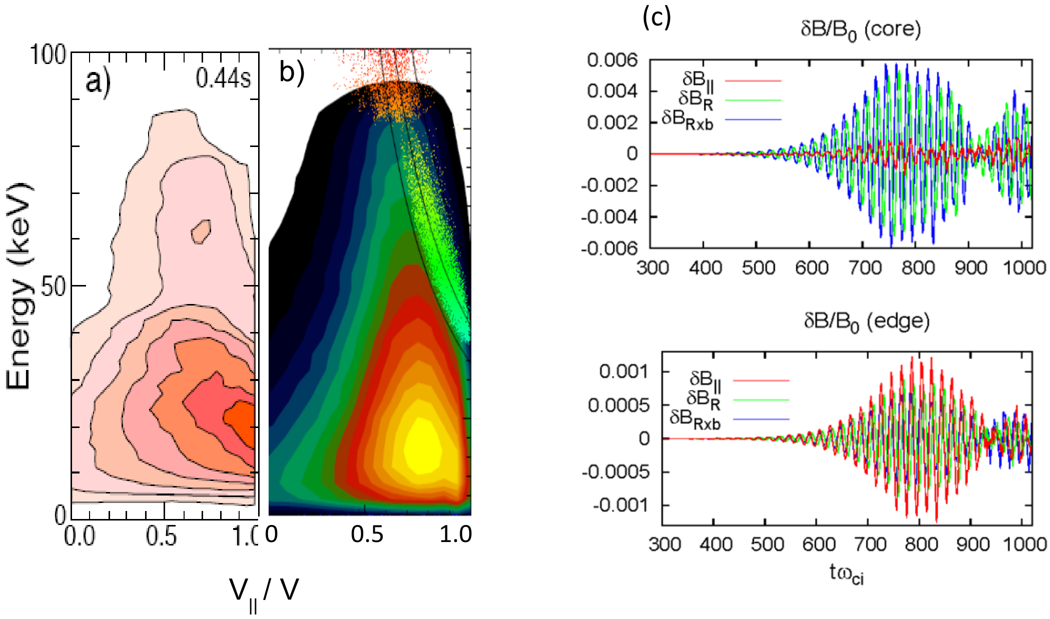


*FIG. 2. (a) TRANSP fast-ion distribution for t=0.44, and (b) HYM fast-ion distribution from n=-11 GAE simulations (t=0.44s); resonant lines are shown; colour dots show resonant particles. (c) Time evolution of perturbed magnetic field components from nonlinear simulations for n=-11 GAE.*

In the simulations, the unstable $n = -11$ mode has been identified as a counter-propagating GAE based on a dominant perpendicular component of the perturbed magnetic field in the core (Fig.2c); however, large parallel component $|\delta B_{\parallel}| \sim |\delta B_{\perp}|$ has been found at the plasma edge on the LFS for this mode. Figure 2c shows the time evolution of $\delta B_{\parallel}$ and two components of $\mathbf{\delta B}_{\perp}$ at the core, and close to the plasma edge in the equatorial plane from the same nonlinear simulation. It is seen that in the core, the magnetic perturbations have shear Alfvén wave polarization with dominant $\mathbf{\delta B}_{\perp}$, and the mixed compressional / shear polarization near the plasma edge. Strong coupling between shear Alfvén and compressional perturbations in the NSTX simulations is related to small aspect-ratio, relatively high beta and kinetic effects due to energetic particles. Experimental magnetic measurements at the edge also show the mixed compressional/shear Alfvén polarization for both CAEs and GAEs in NSTX [9].

## 3. GAE STABILIZATION BY OFF-AXIS NEUTRAL BEAM INJECTION

In NSTX-U, an addition of new beam sources injecting fast ions nearly parallel to the magnetic field allowed to effectively modify the fast ion distribution. It has been experimentally demonstrated, in particular, that all unstable GAEs can be completely stabilized with the injection of a relatively small amount of fast ions with $V_{\parallel}/V \sim 1$. Reliable suppression of the counter-propagating GAEs has been observed in most shots, and the measured GAE suppression time ~ few ms was much smaller than slowing-down time (~50ms), suggesting that it takes relatively few high-pitch fast ions to suppress the GAEs.

HYM simulations also show that off-axis neutral beam injection strongly suppresses all unstable GAEs even for a relatively weak added beam. The off-axis beam injection has been modelled 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 varying density. In simulations the fraction of the off-axis beam population of the total beam ion inventory has been varied from 4% to 17%. Figure 3a shows fast ion distribution function for same beam ion parameters as in Fig. 2b, but with added 5% of fast ions with $F_{add}$ distribution. Significant modification of beam distribution function occurs only in a relatively small region of phase space, where $0.8<V\|/V\leq 1$, but this is the region responsible for the GAE instability drive. For a case shown in Fig. 3a, the modes with n= -7 ÷ -10 are completely stabilized, and the n=-11 GAE remains unstable with significantly reduced growth rate, $\gamma/\omega_{ci}=0.5\%$. Complete stabilization of the n=-11 GAE occurs when fraction of fast ions from additional source increases to 7% (Fig. 3b).

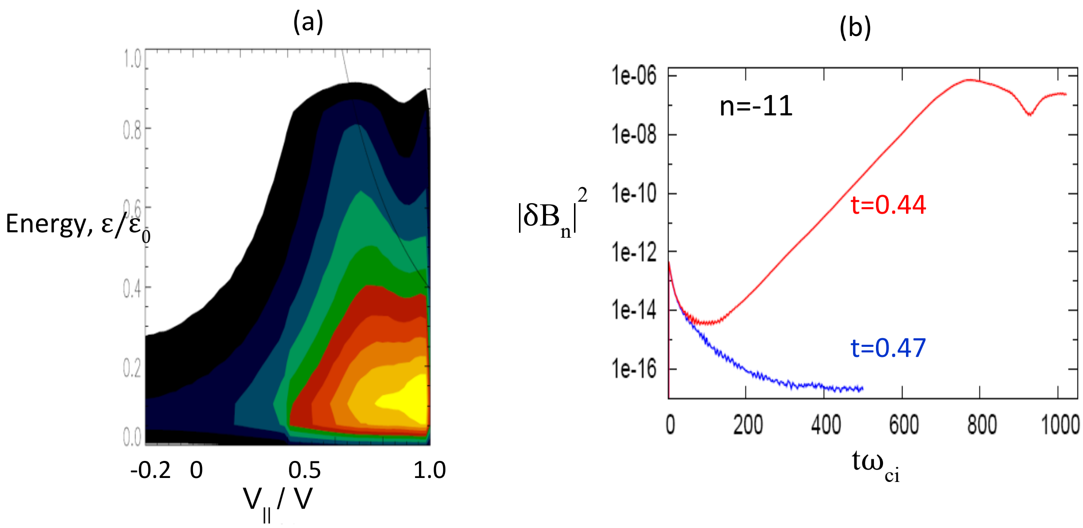


*FIG. 3.(a) HYM fast ion distribution function from n=-11 GAE simulations (t=0.47) including off-axis injected neutral beam ions; (b)Time evolution of n=-11 GAE magnetic energy from linear phase to saturation for t=0.44 NSTX parameters(red), and decay of initial perturbation for stable case corresponding to t=0.47 with additional off-axis beam injection (blue).*

For GAEs with n= -11 ÷ -9 a set of simulations with varying $N_{add}/N_{tot}$ parameter has been performed in order to find the stabilization thresholds. Figure 4 shows the growth rate of the n= -11 ÷ -9 GAEs vs $N_{add}/N_{tot}$ parameter. The unstable n=-11 GAE is stabilized when the fraction of the additional beam ions is larger than 7%. Stabilization threshold is lower for other modes (Fig.4), because cyclotron resonance curves move to higher energies for lower |n|, where the modification of total fast ion distribution is stronger for the same value of $N_{add}/N_{tot}$. Therefore, the simulations show that a complete stabilization of all unstable GAEs (|n|=7÷11) requires an additional beam power significantly lower than what was used in this shot in the NSTX-U (i.e. ~25%), even though the HYM calculated GAE growth rates were relatively large compared to the experimental values.

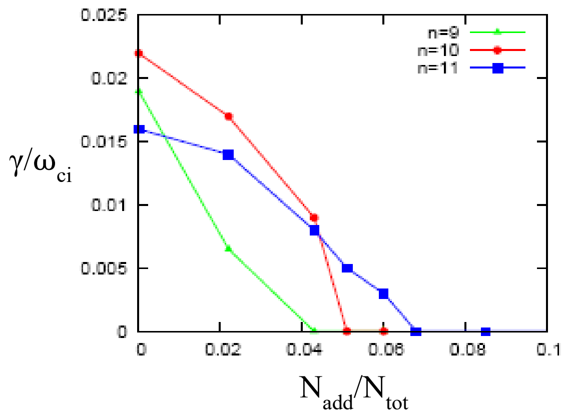


*FIG. 4 Growth rate of the n=-11(blue), -10(red), -9(green) GAEs vs fraction of outboard beam ion population.*

## ACKNOWLEDGEMENTS

Work supported by U.S. DOE Contracts DE-AC02-09CH11466 and DE-SC0011810. The simulations were carried out at the National Energy Research Scientific Computing Center (NERSC).

## REFERENCES

[1] FREDRICKSON, E.D. ., BELOVA, E., BATTAGLIA, D., et al., Suppression of Alfvén modes through additional beam heating, Phys. Rev. Lett. **118** (2017) 265001.
[2] FREDRICKSON, E.D., GORELENKOV, N.N., CHENG, C.Z., et al., Observation of Compressional Alfvén Modes During Neutral-Beam Heating on the National Spherical Torus Experiment, Phys. Rev. Lett. **87** (2001) 145001.
[3] GORELENKOV, N.N., FREDRICKSON, E., BELOVA, E., et al., Theory and observations of high frequency Alfven eigenmodes in low aspect ratio plasma, Nucl. Fusion **43** (2003) 228.
[4] STUTMAN, D., DELGADO-APARICIO, L., GORELENKOV, N.N., et al., Correlation between Electron Transport and Shear Alfvén Activity in the National Spherical Torus Experiment, Phys. Rev. Lett. **102** (2009) 115002.
[5] BELOVA, E.V., GORELENKOV, N.N., CHENG, C.Z., Self-consistent equilibrium model of low aspect ratio toroidal plasma with energetic beam ions, Phys. Plasmas **10** (2003) 3240.
[6] BELOVA, E.V., GORELENKOV, N.N., CROCKER, N.A., et al., Nonlinear simulations of beam-driven compressional Alfvén eigenmodes in NSTX, Phys. Plasmas **24** (2017) 042505.
[7] LESTZ, J.B., BELOVA, E.V., GORELENKOV, N.N., Energetic-particle-modified global Alfvén eigenmodes, Phys. Plasmas 25 (2018) 042508.
[8] FREDRICKSON, E.D., BELOVA, E.V., GORELENKOV, N.N., et al., Global Alfvén eigenmode scaling and suppression: experiment and theory, Nucl. Fusion 58 (2018) 082022.
[9] FREDRICKSON, E.D., GORELENKOV, N.N., BELOVA, E.V., et al., Observation of global Alfvén eigenmode avalanche events on the National Spherical Torus Experiment, Nucl. Fusion **52** (2012) 043001.