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Abstract. In this paper we present data from experiments on NSTX-U where it was shown for the first time that small amounts of high pitch-angle beam ions can strongly suppress the counter-propagating Global Alfvén Eigenmodes (GAE). GAE have been implicated in the redistribution of fast ions and modification of the electron power balance in previous experiments on NSTX. The ability to predict the stability of Alfvén modes, and developing methods to control them, is important for fusion reactor like the International Tokamak Experimental Reactor (ITER) which are heated by a large population of non-thermal, super-Alfvénic ions consisting of fusion generated alphas and beam ions injected for current profile control. A qualitative explanation of the GAE suppression is presented, as well as the results of modeling the GAE suppression with the HYM code. This paper provides a valuable validation of our theoretical understanding of fast-ion-driven instabilities and a promising demonstration of fast-ion driven instabilities via modification of the fast-ion distribution.

1. Introduction

NSTX and now NSTX-U [1] routinely operate with a super-Alfvénic fast ion population from neutral beam injection. This non-thermal population heats the thermal plasma, and is used to control the current profile to enhance plasma stability. However, the non-thermal fast ions also excite a broad range of instabilities, including fishbones, Toroidal Alfvén eigenmodes (TAE), Compressional Alfvén eigenmodes (CAE) and of particular interest for this paper, Global Alfvén eigenmodes (GAE) [2-6]. GAE are shear waves spatially localized near the minimum in the Alfvén continuum, with a frequency just below the minimum, $\omega < \omega_{Amin} = \min[k_{//}(r)\ V_{Alfvén}(r)]$. GAE have been implicated in electron thermal transport [7] and fast ion redistribution [8]. In this paper we will show that the addition of a small amount of nearly tangential fast ions ($V_{//}/V \approx 1$) can robustly suppress the GAE. A similar, but less effective, example of using neutral beams to suppress TAE was seen in the TFTR observations of fusion-alpha-driven TAE. On TFTR, the neutral beams used to heat the plasma and create the alphas were also calculated to add a damping term to the TAE, stabilizing them until the beam injection was ended [9]. On NSTX-U it will be shown that small amounts of high pitch-angle beam ions strongly suppress the counter-propagating GAE.

The new capability to control the fast ion distribution afforded by the new neutral beam sources on NSTX-U was key to demonstrating reliable suppression of the ctr-propagating Global Alfvén eigenmode (GAE). NSTX-U has six beam sources, the original three from NSTX with tangency radii inboard of the magnetic axis ($R_{mag} \approx 1.1$ m) at $R_{tan} \approx 0.7$m, 0.6m and 0.5m, (labeled 1a, 1b, 1c, respectively), and three new outboard sources with R_{tan} =

1.3m, 1.2m and 1.1m (labeled 2a, 2b, 2c, respectively). A sketch of the neutral beam geometry is shown in Fig. 1. The green lines show the trajectories of the original, "inboard" neutral beam lines and the red lines show the trajectories of the new, "outboard" neutral beam lines. The approximate magnetic axis location for this shot ($R_{mag} \approx 1.05$ m) is shown in black. All of the outboard neutral beams inject fast ions onto trajectories largely parallel to the magnetic field, thus with pitch, $0.8 < V_{||}/V < 1$. It should be noted, however, that the fast ion distributions from sources 2b and 2c are still peaked on the magnetic axis and only 2a has created a beam beta that is peaked off-axis.

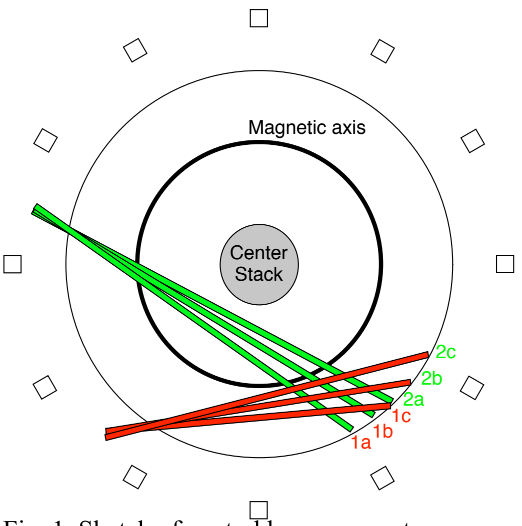

Fig. 1. Sketch of neutral beam geometry. Original NSTX beams in green, labeled 1a, 1b, 1c, new beams for NSTX-U shown in red labeled 2a, 2b and 2c.

2. Suppression of GAE

During the development of target plasmas in the initial commissioning of NSTX-U it was noticed that injection of any of the three new beam sources, with tangency radii larger than the radius of the magnetic axis, would effectively suppress the counter-propagating GAE. Figure 2 shows one of many examples where the addition of the new neutral beam source suppresses existing GAE. This is a 0.6 MA target plasma with a nominal 0.65 T toroidal field and, initially, two neutral beam sources injecting a total of 3.3 MW of heating power. The plasma density is peaked, with central density of $\approx 3.3 \times 10^{19}/m^3$ and the peak electron and ion temperatures are ≈1.7 keV. The core rotation frequency is ≈ 28 kHz. A spectrogram of magnetic fluctuations from the toroidal array of Mirnov coils is shown in Fig. 2a. The toroidal mode numbers are indicated by colors, with the dominant modes being n=-10 (green) and n=-11 (blue). There are also weaker n=-8, -9, -12 and -13 modes. The modes are propagating counter to the beam injection, toroidal rotation and plasma current direction with a lab-frame frequency of ≈1.25 MHz at the analysis time of 0.44s. The counter-propagation is consistent with a model predicting a Doppler-shifted cyclotron resonance (in the resonant beam ion frame, the mode frequency is equal to the ion cyclotron frequency). Correcting for the plasma

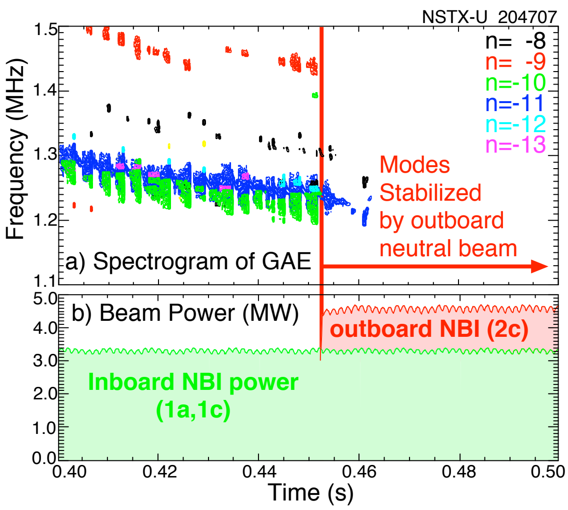

Fig. 2. a) color-coded spectrogram showing ctr-propagating GAE activity. Dominant modes are n=-10 (green) and n=-11 (blue). b) green curve is inboard beam power, red curve is off-axis beam power (source 2c).

rotation frequency, the mode frequency in the plasma frame is ≈ 1.5 MHz or ≈ 0.35 f_{ci}.

At 0.45s a third neutral beam source (2c) is added (Fig. 2b, red curve), and the GAE are suppressed as can be seen in Fig. 2a. The third neutral beam source adds only ≈1.3 MW of additional heating power; making up ≈28% of the total NBI heating power after 0.45s. The suppression of GAE activity begins nearly simultaneously with the third source injection; on a timescale much shorter than the fast-ion slowing down time of ≈ 100 ms. By 0.46s, 8 ms after outboard source injection started, the neutron rate, a measure of the confined fast ion population, has increased ≈ 6%, confirming that a relatively small perturbation to the fast ion population can suppress the GAE.

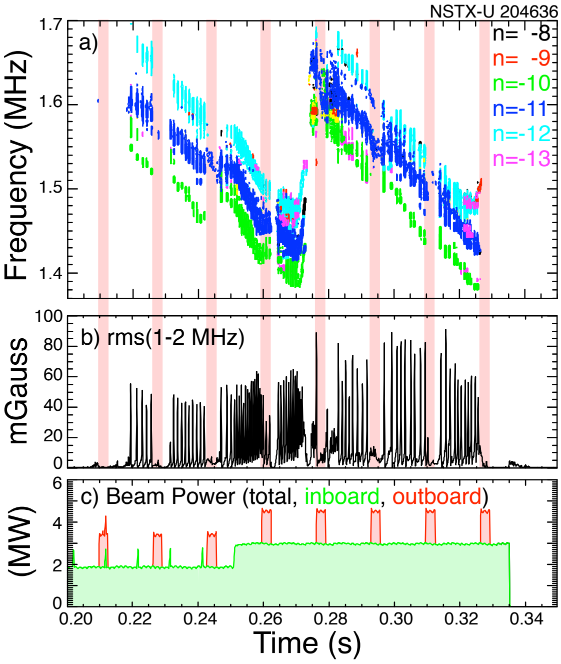

Fig. 3. a) color-coded spectrogram showing GAE activity. Dominant modes are n=-10 (green), n=-11 (blue), n=-12 (cyan), b) rms amplitude of GAE, pink bars indicate when outboard source is on, c) injected beam power, green is total inboard source power, red shows outboard beam pulses (source 2b).

The rapid suppression of the GAE is demonstrated more clearly in Fig. 3. In this shot a sequence of beam pulses with ≈ 3 ms duration are injected every 16 ms into a beam heated plasma with GAE activity. In Fig. 3a it is seen that the dominant modes are n=-10 (green), -11 (blue) and -12 (cyan). The secular variation in mode frequency, including the jump at 0.27s, is consistent with the evolution of the inferred q-profile (through $k_{||}$) and plasma rotation through the Doppler frequency shift. The pink bars indicate when the 3rd source is on. In Fig. 3b is shown the rms GAE amplitude showing bursting modes, similar in amplitude to the GAE bursts shown in Fig. 2. The bursts are completely suppressed with injection of the 3rd (outboard) source (Fig. 3c), with the exception of the fourth beam pulse during which there are two weaker GAE bursts. This clearly demonstrates that suppression can occur on a millisecond timescale and very few additional fast ions are needed to suppress the modes.

3. Theoretical analysis

The unperturbed fast ion distribution functions for the plasma shot shown in Fig. 2 are calculated with the TRANSP code and are shown in Fig. 4 at 0.44s and at 0.47s, ≈10 ms before and ≈20 ms after the addition of the third source. The effects of the GAE and TAE on the fast-ion population are not incorporated in the calculations of the fast ion distributions, however, the short timescale needed for the outboard source to suppress the GAE suggests that there would be little time for modification of the distribution of fast ions injected from the third source before the GAE were suppressed. Comparison of Figs. 4a and 4b shows that the third neutral beam predominantly adds resonant fast ions with pitches greater than ≈0.9.

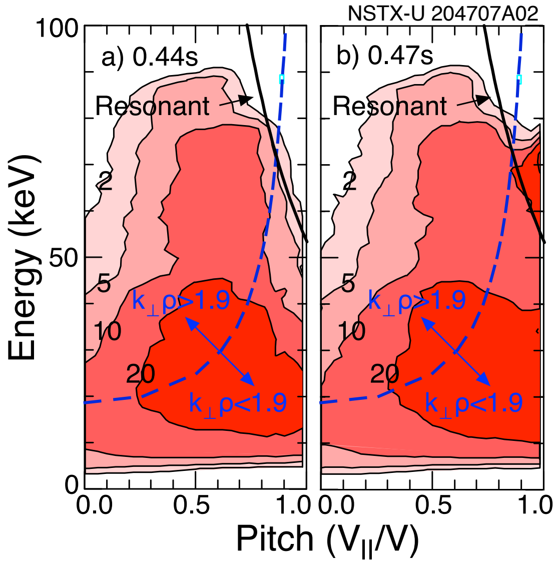

Fig. 4. TRANSP fast-ion distributions for before and after the outboard beam injection. The dashed blue line indicates the boundary between fast ions which drive or damp the mode. Distribution functions are at the minimum of the continuum for the n=-11 mode. Contours as label in units of 10^7 /cm^3/eV/dA.

We can qualitatively understand the GAE suppression through an analytic model of GAE stability [6], an approximate dispersion relation for GAE, and the Doppler-shifted ion cyclotron resonance condition. The model predicts that for $k_\perp\rho_L < 1.9$, the resonant fast ions will be stabilizing, and destabilizing for $1.9 < k_\perp\rho_L < 3.9$, where ρ_L is the Larmor radius of the resonant energetic fast ions. We can estimate $k_{||}$ and $k_\perp$ from the approximate GAE dispersion relation, $\omega_{mode} \approx \min\{\mathrm{abs}[k_{||}(r)\ V_{Alfvén}\ (r) + |n|\omega_{rot}(r)]\}$, by solving to find the magnitude of $k_{||}$, where $|k_{||}| = |n/R - m/qR|$, $k_\perp \approx m/r$. The GAE are measured to be counter-propagating, thus in these expressions $k_{||} < 0$. The resonance condition for fast ions is evaluated locally from $\omega_{mode}+|k_{||} \pm s/qR\ |V_{b||}= \omega_{ci}$, where $V_{b||}$ is the parallel beam ion velocity and s is an integer. The strongest drive comes from the side-band resonances, $s = \pm 1$ [6]. The fast ions satisfying the resonance condition are indicated in Fig. 4a and 4b by the solid black lines. Along this line, as the pitch gets larger, the perpendicular energy of the fast ions decreases, eventually reaching the boundary between destabilizing (low pitch) and stabilizing (high pitch). That boundary is indicated by the dashed blue lines. As can be seen by comparing Figs. 4a and 4b, the injection of the outboard source adds more fast ions to the stabilizing part of the resonance curve. This is a local, very qualitative evaluation using an approximate q-profile. A more comprehensive analysis requires a stability code which can evaluate the Doppler-shifted cyclotron resonant drive.

The example of GAE suppression shown in Fig. 2 has been modeled using simulations with the HYM code using reconstructed equilibria and the fast ion parameters as calculated in the TRANSP code. The cyclotron resonance drive means that modeling the mode stability requires a code which uses a full orbit beam-ion model. The HYM code [10-12] is an initial value, hybrid code in toroidal geometry which treats the beam ions using a full-orbit, delta-f particle model. The background plasma is represented by one-fluid resistive MHD. The distribution function is input to the code in an analytic form based on the calculation in

TRANSP which doesn't include anomalous fast ion diffusion which might be present, for example, from the strong TAE avalanching present.

Simulations with the HYM code find unstable GAE with n=-7 through -12 (Fig. 5a) using plasma equilibrium parameters and the fast-ion distribution function calculated at 0.44s, before the modes were suppressed, consistent with experiment. The linear growth rates for the modes are shown in Fig. 5a, with the fastest growing mode being n=-10, in good agreement with the experimental measurements. The mode frequencies are shown in Fig. 5b (red curve). HYM doesn't include the bulk toroidal rotation, so an approximate Doppler correction is made to the simulated mode frequencies (blue curve) and which are in good agreement with the experimental frequencies (blue ∗). The polarization of the magnetic fluctuations shows that the modes have shear polarization near the peak in mode amplitude, showing that the modes found by HYM are in fact GAE and not Compressional Alfvén eigenmodes. Further HYM runs, using parameters from the TRANSP run at 0.47s have found that the modes with n = -7 to -11 have become stable, consistent with the observed suppression of the GAE.

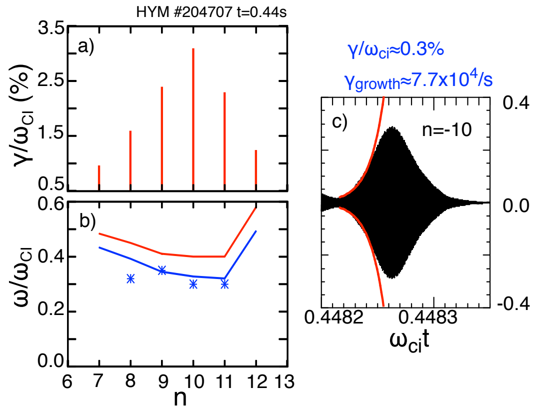

Fig. 5. (a) Growth rates and (b) frequencies of unstable counter-GAEs from HYM simulations for t=0.44s. Blue line is Doppler-shift corrected frequencies, points – experimental values, c) GAE burst with fit to exponential growth (red).

Experimental estimates of the drive and damping rates for the GAE can be made from the growth and decay rates of the GAE bursts, Fig. 5c. The bursts last for about 70 μs. The growth rate, γ_{growth}, of the burst is measured to be about 13 μs and the decay rate, $|\gamma_{decay}|$, is about 16 μs. With the assumption that the damping rate is constant, and that the growth rate of the burst is $|\gamma_{growth}| \approx |\gamma_{drive}| - |\gamma_{damp}|$, and that $|\gamma_{damp}| \geq |\gamma_{decay}|$, then $\gamma_{drive} \geq |\gamma_{growth}| + |\gamma_{decay}|$. For comparison to the simulation results below, those numbers are normalized to the ion cyclotron frequency of ≈2.7 x 10^7 radians/s to get $\gamma_{growth}/\omega_{ci} \approx 0.3\%$ and $\gamma_{drive}/\omega_{ci} \approx 0.5\%$.

3. Summary

Three neutral beam lines were added to the original three beam lines on NSTX during the recently completed upgrade from NSTX to NSTX-U,. The new sources inject higher pitch-angle fast ions, allowing much greater flexibility in generating the fast ion distribution. In the first operational campaign on NSTX-U, the near tangential fast ions effectively suppressed the GAE. The GAE are one of the common beam driven instabilities seen on NSTX, and are correlated with enhanced core electron thermal transport. Analysis of one of these NSTX-U discharges with the HYM code at a time during strong GAE activity finds that the n = -10 and n = -11 ctr-propagating GAE are most unstable, in good agreement with experimental measurements. HYM predicts that the GAE have strong growth rates of 2-3% of the ion-cyclotron frequency. The experimental growth rates are difficult to measure, but appear to be significantly smaller (≈ 0.5% ω_{ci}), possibly because the distribution function used in HYM is unperturbed. The predicted Doppler-corrected mode frequencies are between 0.3 ω_{ci} and 0.35 ω_{ci}, in very good agreement with the observed mode frequencies. HYM simulations using the TRANSP fast-ion distribution functions which include one of the new beam sources find that the n = -7 through n = -11 modes become stable. These results suggest that stabilization may be due to an increase of the population of deeply passing particles (with small Larmor radius) which have a stabilizing effect on the GAEs. Further work is required to improve understanding of the suppression mechanism. The agreement in unstable mode numbers and mode frequencies between theory and experiment in these initial results from the HYM code with the experimental measurements provide a strong validation of the HYM code physics, providing confidence in the use of HYM to predict stability of plasmas on ITER.

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