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by

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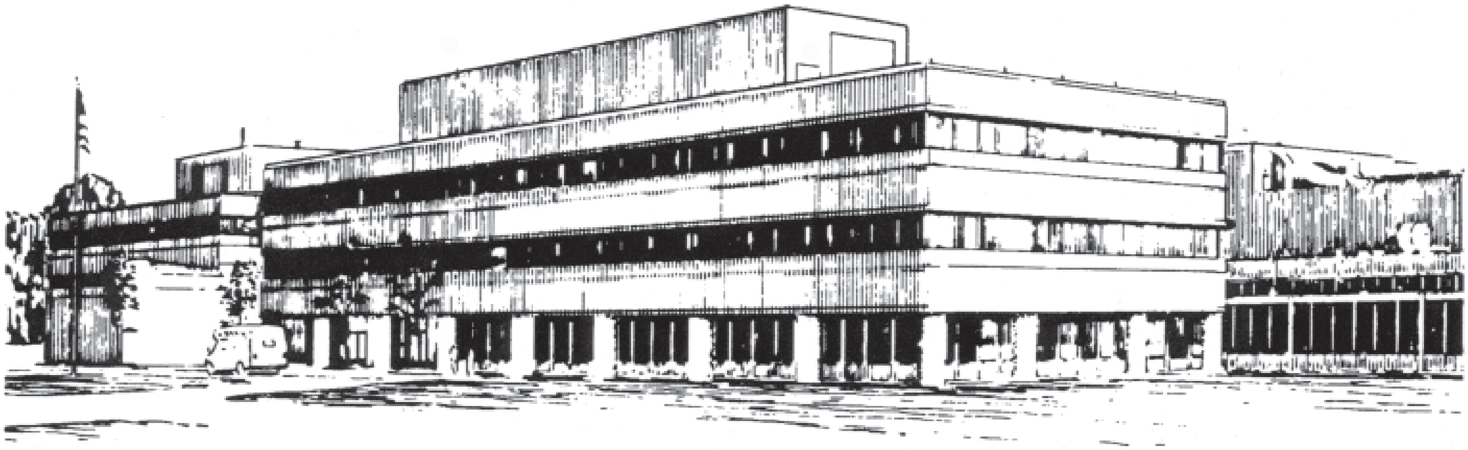

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Beam Ion Driven Instabilities in NSTX

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Abstract

A low-field, low aspect-ratio device such as National Spherical Tokamak Esperiment (NSTX) is an excellent testbed to study the ITER relevant physics of fast particle confinement, which is of major importance for burning plasmas. The low Alfven speed in NSTX offers a window to the super-Alfvenic regime expected in ITER. Effects such as the large finite Larmor radius (FLR), orbit width, strong shaping, and high thermal and fast-ion betas make this effort a greater challenge. We report on the linear stability of different Alfven eigenmode (AE) branches and compare theory with experimental data.

Low frequency magnetohydrodynamic (MHD) activities $\sim 100kHz$ on NSTX are often observed and identified as the toroidicity-induced AEs (TAE) driven by beam ions. Sometimes they are accompanied by beam ion losses in high confinement mode (H-mode), high $q(0)$ plasmas. Numerical analysis using NOVA-K code shows good agreement with the experimental data. The TAE instability was compared in experiments on NSTX and DIII-D. With similar plasma conditions we tested the theoretical prediction that the toroidal mode number of the most unstable TAEs scales with the machine minor radius, $n \sim a$. In NSTX, TAEs are observed with $n = 1 - 2$, whereas in DIII-D $n = 2 - 6$. The confirmation of n scaling helps to validate the predictive capabilities of theoretical tools (NOVA-K) for studying ITER plasmas.

In the high frequency range, recent observations of rich sub-ion cyclotron frequency MHD activities in NSTX suggest that new instabilities are excited, which we identify as Global shear AEs (GAEs). Similar to the compressional AEs (CAEs), GAEs are destabilized by the Doppler shifted cyclotron resonance in the presence of $80keV$ neutral beam injection. To simulate GAE/CAEs in realistic NSTX plasma conditions we have developed a nonlinear hybrid kinetic-MHD code, HYM, which is capable of computing the mode structure, saturation, and energetic particle transport.

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I. INTRODUCTION

Alfvén eigenmodes (AE) have been of interest to fusion researchers for the last four decades (see for instance [1]). Low frequency Alfvén instabilities driven by the spatial energetic particle pressure gradient can limit energetic particle confinement in toroidal fusion devices and thus may be of main concern for a fusion tokamak reactor such as ITER [2]. Among many AEs observed in tokamaks, toroidicity-induced Alfvén eigenmodes (TAEs) [3, 4] are considered to be the most efficient in transporting fast ions along the plasma minor radius. AEs are also of interest since they can be used for the diagnostics of the plasma and fast ion parameters [5, 6].

TAEs in low-aspect ratio tokamaks (or spherical tokamaks, STs) have been predicted [12] and observed in START [13] and NSTX experiments [19]. Typically the range of NSTX operational parameters are: toroidal current $I_p = 0.7 - 1\,MA$, toroidal field $B_{g0} = 3 - 5\,kGauss$, central electron density $n_{e0} = 1 - 5 \times 10^{13}\,cm^{-3}$, central electron temperature $T_{e0} \lesssim 1\,keV$. The plasma is heated with a deuterium beam with power of $P_b = 1.5 - 3\,MW$ and injection energy usually $E_{b0} = 80\,keV$. With such a low magnetic field, the ratio of beam ion velocity to the Alfvén velocity is typically $1 < v_{b0}/v_{A0} \lesssim 3$. This parameter is critical in determining the stability of TAEs, i.e., fast ions need to be superalfvenic to excite the mode. In NSTX, the neutron flux drops by as much as 10 to 15% due to TAEs [19]. TAEs often have bursting behavior of the amplitude which is sharply increasing on a time scale of $\sim 1\,msec$. The measured TAE amplitude at the plasma edge is up to $\delta B/B = 3 \times 10^{-4}$. Multiple modes are often present in the experiments. High ratio of v/v_{A0} in NSTX plasmas provides a unique opportunity to study the physics of TAE instabilities relevant to burning plasmas, such as those in ITER.

Linear theory of TAE instability predicts that the most unstable TAE mode numbers are determined by the finite orbit width effects [14–16] so that $k_\perp \Delta_b \sim 1$ holds for the most unstable modes. The plateau in the dependence of the TAE drive on toroidal mode number n is achieved for the range:

$$n_{min} < n < n_{max}, \tag{1}$$

where $n_{min} \simeq r n_{max}/R$, and $n_{max} \simeq r\omega_{c\alpha}/q^2 v_A$. This agrees with the numerical NOVA code [4] simulations in which Finite Orbit Width (FOW) and Finite Larmor Radius (FLR) effects are included [17]. Changing the parameter $n/z_h \sim k_\perp \Delta_b$ by changing particle charge (where it was assumed that $m \simeq nq$), it was found that at $n < n_{min}$ fast ion driven growth rate scales like $\gamma_d \sim n$, whereas at $n > n_{max}$, it decreases as $\gamma_b \sim n^{-1}$. The latter scaling confirms the results of Ref. [15]

but is different from analytical work of Ref. [16], where $\gamma_b \sim n^{-2}$ was predicted.

One can see from Eq.1 that the range of toroidal mode numbers of the most unstable TAEs is shifted toward high n in burning plasmas with large machine size, such as ITER. This was verified in a specially designed similarity experiment on NSTX and DIII-D, in which plasma parameters were created similar with the exception of the major radii. We analyze these experiments in section II with the help of the ideal MHD code NOVA [4] and hybrid kinetic perturbative code NOVA-K [17, 18] in an attempt to recover observed scaling. This helps to validate the application of NOVA and NOVA-K codes to future burning experiments.

High frequency AEs, at or above the ion cyclotron frequency, driven by the beam ions have been observed in NSTX and predicted to be excited by the velocity space positive gradients [7–10]. Initial observations of high frequency modes and their analysis showed that the instability dispersion is consistent with the dispersion of compressional Alfvén eigenmodes (CAE). Since the CAE is driven by the gradient in the velocity space one can expect that it will result in fast ion energy diffusion. If many high frequency AEs are excited at sufficiently large amplitude they interact with the bulk plasma ions via the stochastic damping mechanism opening a channel for direct energy transfer from fast ions to plasma ions avoiding the heating of plasma electrons [11].

Recently new features of the high frequency magnetic fluctuation spectrum were observed in NSTX, which suggest that new instabilities with the dispersion of a shear Alfvén branch are excited. In section III are presented the experimental observations, development of analytical theory, and numerical tools for the analysis of these new instabilities which are identified as global Alfvén eigenmode (GAE).

II. TOROIDICITY-INDUCED ALFVÉN EIGENMODES IN NSTX AND DIII-D

A specially designed similarity experiment between NSTX and DIII-D [20] was performed to verify the theoretical predictions of scaling the most unstable toroidal mode numbers with the machine size. In order to do that the plasmas in both tokamaks were created to be similar. However, the major radii and safety factors were considerably different in NSTX and DIII-D. The table I shows the main plasma and fast ion parameters for NSTX and DIII-D and how they are compared to the ones of ITER. Critical for the TAE stability is the ratio of fast ion velocity to the Alfvén velocity, which is similar in all the compared plasmas. Also shown in the table is the estimate of the maximum toroidal mode number expected for each machine (Eq. 1). The difference in estimates for NSTX and DIII-D plasmas comes primarily from the different safety factor values.

	R	a	B_0	β_{i0}	$\beta_{b,\alpha 0}$	v_{b0}/v_{A0}	$a/\rho_{b,\alpha 0}$	n_{max}
	(m)	(m)	(T)	(%)	(%)			
NSTX	0.77	0.6	0.5	1.1	4.2	1.85	6	1
DIII-D*	1.63	0.6	0.63	2.6	4.4	1.5	6	4
ITER-FEAT, beam ions	6.2	2	5.3	2.2	1.2	1.4	50	15
alphas					0.7	1.8	40	15

Table I: Plasma parameters in the NSTX/DIII-D similarity experiments and in the planned ITER experiment.

As predicted, the observed most unstable mode numbers are higher in DIII-D. The dependence of the expected n_{max} versus predicted ones is shown in Fig. 1 (this figure is reproduced from Ref. [20]). Based on these results, it is concluded that the most unstable mode numbers scale with a/q^2. The experimental toroidal mode numbers shown in Fig. 1 are for TAEs with nearly constant frequencies; the toroidal mode number with the largest edge magnetic field amplitude is shown. Another difference between NSTX and DIII-D is that the instabilities often chirp rapidly in frequency in NSTX but this phenomenon is rare in DIII-D.

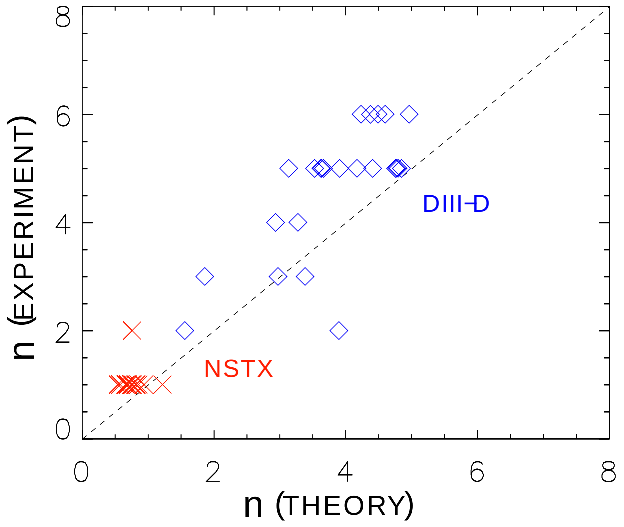

Figure 1: Observations of the most unstable TAE toroidal mode numbers versus those theoretically predicted.

A. Application of NOVA to similarity experiments

Linear TAE stability is simulated with NOVA and NOVA-K codes. These codes implement a perturbative method in which the ideal MHD mode structure of the TAEs is calculated first by the NOVA code [4]. The plasma parameters are modeled with the TRANSP code [21]. Then the mode structure is analyzed with the hybrid kinetic code NOVA-K [17, 18], in which the mode damping and driving mechanisms are evaluated. Fast-ion drive includes FOW and FLR effects. In the calculations the following damping mechanisms are incorporated: ion and electron Landau damping, radiative damping, and trapped electron collisional damping.

Since the interactions of trapped and passing beam ions with TAEs are different, it is important to have the ratio of trapped to passing particle densities similar in both experiments. This was achieved by adjusting the angle of neutral beam injection (NBI) [20]. The distribution function of beam ions is calculated by TRANSP. As shown in Fig. 2, the ratio of trapped/passing particles is approximately the same in both experiments. Particles injected at $80keV$ into a relatively narrow pitch angle window slow down and scatter in pitch angle, so that the pitch angle width is increasing. The beam distribution function is modeled by TRANSP Monte-Carlo code and has statistical errors, which are difficult to handle in NOVA codes where derivatives of the distribution function are calculated analytically. Thus the numerical distribution function is fitted into the following analytical form

$$f_b(\psi, v, \chi) = n(\psi)\, C \frac{e^{-(\chi-\chi_0)^2/\delta\chi(v)^2}}{v^3 + v_*^3},$$

where C is the normalization constant (details of the distribution function model will be published elsewhere).

The results of the stability analysis using NOVA and NOVA-K codes are shown in Fig. 3. The TAE unstable range of toroidal mode numbers is shifted to high-n numbers in DIII-D as predicted by the theory. Note that the anisotropic distribution is important for reproducing the observed unstable mode numbers, whereas NOVA-K calculations with an isotropic distribution function does not predict unstable modes observed in experiment. The main damping mechanisms in calculations turned out to be the ion Landau damping and radiative damping. In ITER ion Landau damping is expected to be the main damping mechanism [24].

What are experimental (and modeling) uncertainties in damping/growth rate simulations? From the calculations of the growth and damping rates it follows that $\gamma_d/\gamma_b < 1$ for low n modes. It means that in the plasma there may be extra linear or nonlinear damping. The latter is due to

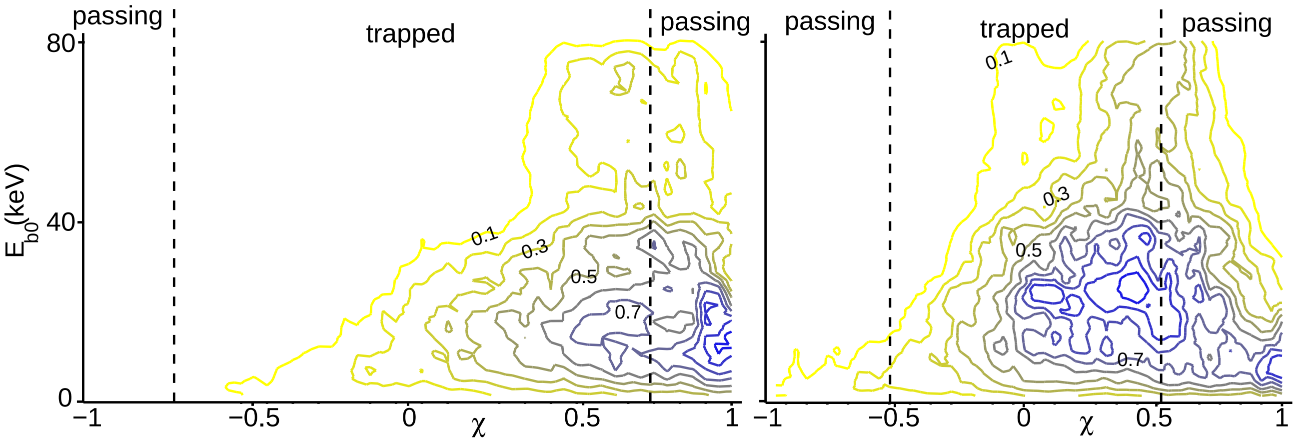

Figure 2: Contours of the beam ion distribution function in NSTX (left) and DIII-D (right) in the plane of ion energy and pitch angle, taken at the midplane and at the minor radius $r/a = 1/2$. Shown also as dashed lines are the boundaries between the passing and trapped regions.

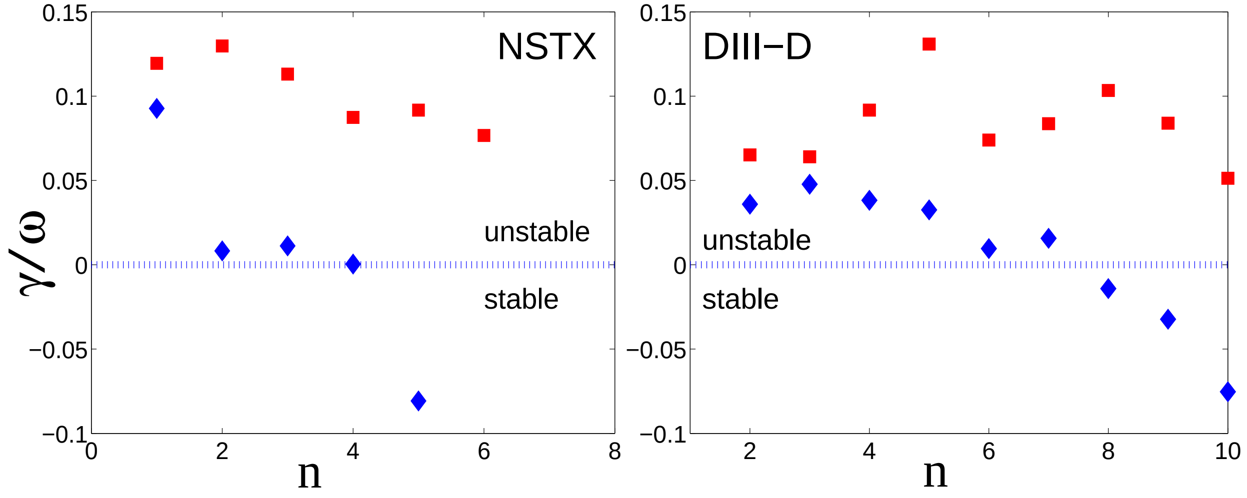

Figure 3: The results of NOVA simulations of TAE growth rates in NSTX (left) and DIII-D (right). The fast ion contribution to the growth rates of the most unstable modes are indicated with a ■ wheras the net growth rate with the damping terms included is shown as ♦.

the change in the distribution function of fast ions. Let us introduce this additional damping term γ_{dx} and estimate it based on the following. In experiments there were observations of near steady TAE amplitude evolution in both NSTX and DIII-D. Low amplitude $\delta B/B \sim 10^{-5}$ at the plasma edge was measured. On the other hand, theory predicts that TAE amplitude at the edge is close within an order of magnitude to the peak mode amplitude at the center. In NOVA-K nonlinear mode saturation theory is included, so that the amplitude of steady state mode can be predicted [22, 23]. It follows from this theory that TAEs with the amplitude observed in the experiments must be near threshold. The extra damping term γ_{dx} should satisfy the near threshold excitation condition $\mathcal{R} \equiv -(\gamma_d + \gamma_{dx})/\gamma_b \simeq 1$, i.e., $\gamma_{dx} = -\mathcal{R}\gamma_b - \gamma_d$. Note that for the measured amplitudes the proximity of $\mathcal{R}$ to one depends on the amplitude but is very small. NOVA-K suggests that $1 - \mathcal{R} \simeq 10^{-2} - 10^{-3}$. As simulations show, γ_{dx} is less than 20% of the drive for medium/high-n's, which is illustrated in Fig.4. However low-n modes are very sensitive to the details of the $q-$profiles. For example, in the case of DIII-D $n = 2$ Alfvén continuum the gap is open, which means that there is no continuum damping. A small change in q or density profile may increase the damping of low-n modes and reduce the value of γ_{dx}.

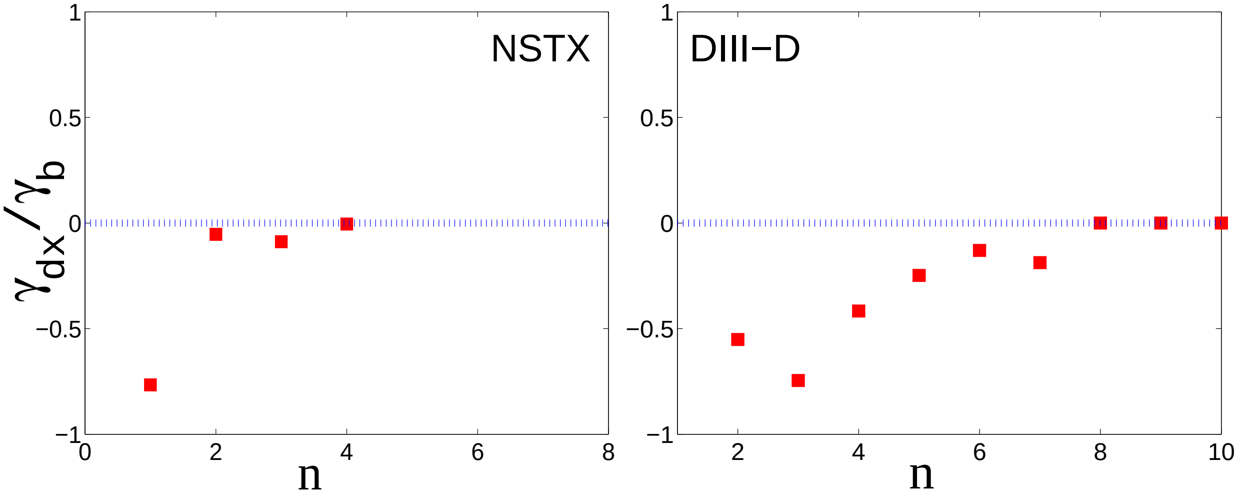

Figure 4: Model of extra damping required to make a prediction of near threshold TAE excitation.

For the medium to high-n numbers, NOVA code seems to fairly predict the threshold of TAE instability in both NSTX and DIII-D. This helps to validate the study of burning plasmas in ITER using NOVA codes, such as a study done recently Ref. [24]. This study shows that TAEs are expected to be weakly (marginally) unstable in ITER nominal plasmas with central temperatures of $T_{i0} = 20keV$ and fusion alpha central beta $\beta_{\alpha 0} = 0.7\%$ if only α-particles are included in the drive. Plasmas with $T_{i0} > 20keV$ are likely to be unstable with the respect to TAEs due to α's. In addition to energetic fusion products in ITER $1MeV$ tangentially injected beams are planned to be used to drive the plasma current. Beam ions are superalfvenic and can drive TAE with as much growth rate as $\alpha-$particles. It is shown in Ref. [24] that NBI drive makes TAEs unstable in much wider toroidal mode number ranges. Lowering NBI energy to $0.5MeV$ reduces TAE drive, whereas $0.5 MeV$ energy is enough for good beam penetration into a plasma.

III. HIGH SUB-ION CYCLOTRON FREQUENCY MODES IN NSTX

A. Observations of GAEs in NSTX

Global Alfvén eigenmodes are formed below (in frequency) the minimum of the Alfvén continuum with approximate frequency given by the expression $\omega \simeq \omega_{Amin} = \left(k_{||}(r)v_A(r)\right)_{min}$ [25]. Here and below subscript min means that the value is taken at the minimum ω_{Amin}. The GAE eigenfrequency is slightly shifted downward from ω_{Amin}, and the shift depends on the q and density profiles. GAE is localized radially near the minimum ω_{Amin} and is dominated by one poloidal harmonic m. With a typically flat q profile, the Alfvén continuum has a minimum at the plasma center, so that $\omega \simeq \pm v_{A0} \left(m/q_0 - n\right)/R_{ax}$, where R_{ax} is the major radius of the magnetic axis. One can note that if q is evolving in time, eigenfrequencies of GAEs with different combinations of (m,n) will have different time dependencies.

Mode structure of GAE as it is calculated by NOVA code is shown in Fig. 5 where an Alfvén continuum for $n = 3$ is also shown. The frequency of the continuum is shown as normalized to the Alfvén frequency $\omega_{A0} = v_{A0}/q_a R_0$, where q_a is the safety factor at the plasma edge, and R_0 is the major radius of the plasma geometrical center.

B. Theory of GAE instability

GAE instability is driven by NBI ions and has been recently studied in details in Ref. [10]. This theory is outlined here. Due to tangential NBI injection in NSTX, the distribution function of beam ions has a positive gradient in the velocity space. It provides an energy source for the instability and forms a “bump on tail” in the $v_\perp$ direction. Particles are in Doppler shifted cyclotron resonance with the mode $\omega - \omega_{cb} - k_{||}v_{||} - k_\perp v_{db} = 0$. Theory predicts that GAEs are unstable if $2 < (\omega/\omega_{cb})\left(v_{\perp b0}/v_A\right)\left(k_\perp/k_{||}\right) < 4$, and bump-on-tail width in $v_\perp$ satisfies $\delta v_{\perp b} < 2 v_A \omega_{cb}/\omega$. Main GAE damping is continuum damping [26]. For high-m GAEs it is small [10]

$$\frac{\gamma_d}{\omega} \sim \left(\frac{r_2}{r_s}\right)^{2m+\delta},$$

where following notations of Ref.[10], r_2 is the mode location, r_s is the minor radii of the $m+1$ continuum branch, where GAE has singularity, $\delta = O(1)$. This is because the singularity is always

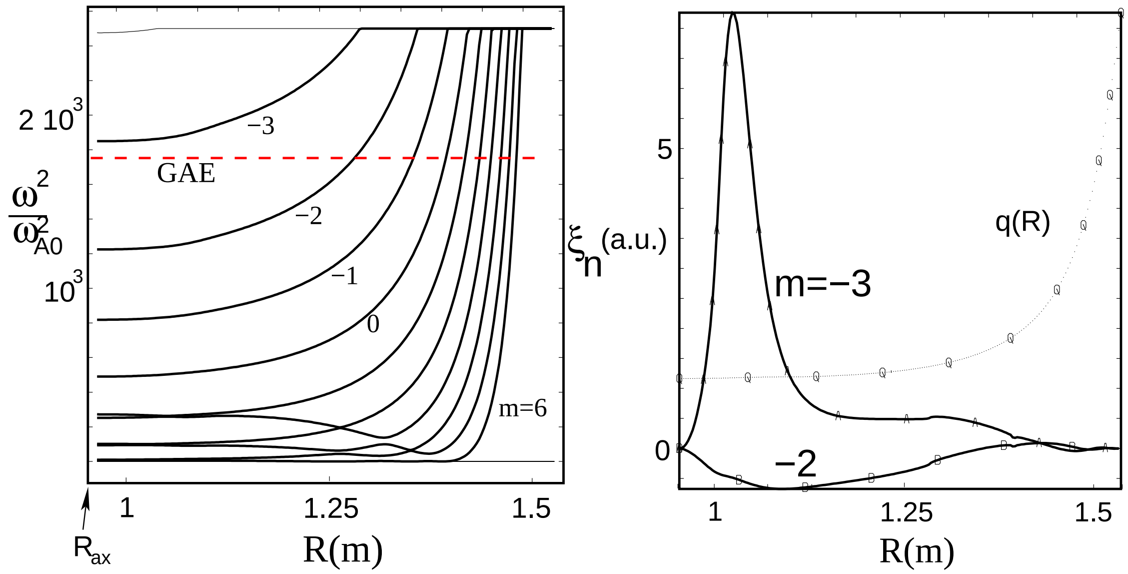

Figure 5: An Alfvén continuum (left) and a GAE mode structure (right) shown for $n = 3$ in a typical NSTX plasma. The frequency of GAE is shown as a dashed line in the Alfvén continuum.

outside the mode localization in minor radius, $r_2/r_s < 1$.

C. HYM nonlinear hybrid code for GAE study

3-D hybrid simulations using HYM code [27, 28] has been employed to study the excitation of AEs by energetic ions in NSTX. The HYM code is a nonlinear, global stability code in toroidal geometry, which includes a fully kinetic ion description. In the numerical model, beam ions are treated with full-orbits implying delta-f method for particle simulations, while the one-fluid resistive MHD model is used to represent the background plasma. These two plasma components are coupled using a current coupling scheme. It is assumed that the fast ion pressure can be comparable to the pressure of the thermal plasma, but the beam ions have low density $n_b \ll n_p$. The effects of the beam ion toroidal and poloidal currents are included non-perturbatively to account for the anisotropic fast ion pressure tensor and to calculate self-consistent equilibria, which serve as an initial condition for the 3-D simulations.

HYM simulations for typical NSTX parameters confirm that for large injection velocities of beam ions, $v_{b0} > 3v_A$, and strong anisotropy in the pitch-angle distribution, there are unstable Alfvén modes. It is found that the most unstable modes for low toroidal mode numbers, $2 < n < 7$, are GAE modes [25]. These modes are found to be localized near the magnetic axis, and have large $k_{||}$ (with $nm < 0$), so that $\omega \sim |k_{||}v_{||}| \sim \omega_{ci}/2$. The perturbed plasma pressure in the poloidal cross section of the NSTX plasma of a GAE mode with $n = 4$ and $m = 2$ is shown in Fig. 6. The poloidal velocity has a vortex-like structure, which is characteristic for shear Alfvén waves. However, in NSTX these modes have a significant compressional component, $\delta B_{||} \sim B/3$, due to strong coupling to the compressional Alfvén wave. Linearized simulations for different n's show that for the most unstable modes, a condition $n + m = 6$ is satisfied (i.e., approximately same $k_{||}$). Several Alfvén modes (with different dominant m) can be excited for each toroidal mode number n as illustrated in Fig. 7. In HYM simulations for $n_b/n_p \simeq 3\%$, the growth rates of unstable GAE modes are found to be of the order $\gamma/\omega_{ci} = 0.002 - 0.01$ with frequencies $\omega/\omega_{ci} = 0.3 - 0.5$, where ω_{ci} is evaluated at the geometrical plasma center. For the mode shown in Figs. 6 and 7, the growth rate was $\gamma/\omega_{ci} = 0.005$ and $\omega/\omega_{ci} = 0.3$.

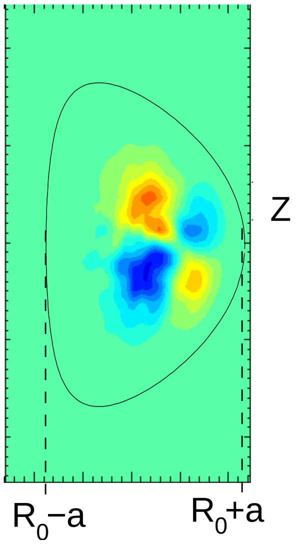

Figure 6: Contours of the fluid pressure perturbation of $n = -4, m = 2$ GAE mode plotted in the poloidal R, Z plane. Shown also is the last closed magnetic surface of NSTX plasma.

IV. CONCLUSIONS

Linear theory and numerical tools such as NOVA/NOVA-K hybrid kinetic codes predict TAE instability in burning plasmas and are shown in this paper to be consistent with experiments in NSTX and DIII-D. From the comparison of computations with the experiments it follows that the most unstable mode toroidal number scales with the minor radius of the plasma. NOVA predicts

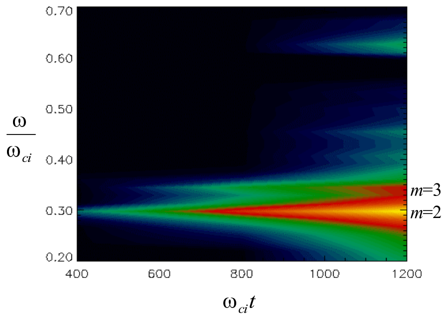

Figure 7: The amplitude evolution of the spectrum of unstable modes with n = 4 as calculated by HYM. Lower frequency peaks of the spectrum correspond to GAE's with m = 2 and 3.

TAEs to be unstable in ITER if driven by fusion alphas in a plasma with $T_{i0} > 20keV$. Calculations also predict that TAEs will be unstable in ITER if NBI drive is included even for $T_{i0} < 20keV$.

New features of sub-cyclotron frequency spectrum in NSTX reveals frequency peaks intersecting in time, which have been identified as global shear Alfvén eigenmode instability driven by NBI ions. GAEs interact with ions via the Doppler shifted cyclotron resonance by the positive gradient in velocity space $v_\perp$ direction of the equilibrium distribution function of confined beam ions ("bump on tail"). Both hybrid code HYM and NOVA code modelings agree with analytical theory on GAE mode structure and dispersion.

V. ACKNOWLEDGMENTS

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