FAST PARTICLE EXCITATION OF TAEs IN NSTX*

N. N. Gorelenkov[1], C. Z. Cheng[1], G. Y. Fu[1], M. V. Gorelenkova[2]
S. Kaye[1], R. Nazikian[1], R. White[1]

[1] *Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543*
[2] *TRINITY, Troitsk, Moscow Region, Russia, 142092*

INTRODUCTION

Toroidicity-induced Alfvén Eigenmodes (TAE) were observed in many experiments on tokamaks including recent DT experiments on TFTR[1] and in spherical tokamak experiments such as START[2] and are believed to result in a degradation of fusion product confinement in a reactor. The unique features of NSTX, such as low aspect ratio, high plasma and energetic particle beta, low Alfvén velocity with respect to beam ion injection velocity, and large Larmor radii present an entirely new regimes for studying energetic particle physics. Proposed NBI ions and high harmonic ICRH in NSTX[4] will produce super Alfvénic fast ions inducing a strong drive for TAEs. For example, NBI ions will be injected at $\mathcal{E} = 80keV$, which gives following estimates for the injected ion velocity and the Alfvén velocity $v_{b0} = 3 \times 10^8 cm/s \gg v_{A0} \simeq 10^8 cm/s$, fast ion Larmor radius $\rho_{Lb}/a \simeq 1/4$, and drift orbit radial width $\Delta_b/a = (q/\epsilon)\rho_{Lb}/a \simeq 1/2$. In this work TAEs in NSTX are analyzed using the improved NOVA-K code[5], which includes fast ion finite orbit width and Larmor radius effects to calculate the stability [6] and predicts the saturation amplitude for the mode using a quasilinear theory[7]. Then the ORBIT code is used[8] to estimate the effect of TAEs on fast neutral beam ions.

LINEAR EIGENMODE STUDY

In NOVA code calculations the conservation of three particle integrals of motion is assumed, which are velocity v, magnetic moment $\mu = v_\perp^2/2B$, and toroidal canonical momentum P_φ. We analysed four NSTX equilibria. The first equilibrium has low central safety factor $q_0 = 0.4$, and $q_{edge} = 15$, which corresponds to TRANSP analysis code[9] run #11112$P60$ at $\langle\beta\rangle \equiv 8\pi \langle p\rangle / \langle B^2\rangle = 10\%$ ($\beta_{tor} \equiv 8\pi \langle p\rangle / B_{\varphi 0}^2 = 34\%$). The second equilibrium has medium $q_0 = 0.7$, $q_{edge} = 16$ at $\langle\beta\rangle = 10\%$. And the third and the fourth equilibria have high $q_0 = 2.8$, $q_{edge} = 12$ at high beta $\langle\beta\rangle = 15\%$ and medium beta $\langle\beta\rangle = 8\%$, respectively. Pressure and density profiles can be presented in the form $P(\psi) = P(0)\left(1-\psi^{1.03}\right)^{1.7}$, $n_e(\psi) = n_e(0)\left(1-\psi^{1.62}\right)^{0.48}$for low-$q_0$ and medium-q_0 cases, while for high-q_0 case we use $P(\psi) = P(0)\left(1-\psi^{1.8}\right)^2$, $n_e(\psi) = n_e(0)\left(1-\psi^{10}\right)^{0.12}$. Vacuum magnetic field is $B_0 = 0.3T$ at the geometrical axis.

Density and safety factor profiles are usually flat near the plasma center creating the aligned gap along the minor radius. Calculations show that Alfvén continuum gap is large due to the effect of strong toroidal coupling and does not close at high beta $\beta \simeq 1$, so that TAEs still can exist. For each toroidal mode number n we found several TAE modes. Caclulations also show that in NSTX TAEs typically have very broad radial structure covering the whole minor radius. Thermal tail ions may be super-Alfvénic at energies $\mathcal{E}_i > 6keV$, which indicates that plasma ion ω_{*i} effects are important but are neglected in our model. Figure 1 illustrates the gap structure, where the frequency of the continuum

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is shown as normalized to the Alfvén frequency $\omega_A = v_{A0}/q_{edge}R_0$, R_0 is the major radius of the geometrical center and v_{A0} is the Alfvén velocity evaluated with the central plasma mass density and magnetic field at the geometrical axis. We note, that higher frequency gaps, i. e. gaps induced by noncircularity are usually closed in NSTX plasma. We performed calculations for toroidal mode numbers $n = 1, 3, 5, 7$. A number of modes were found: 6 for low-q_0, 22 for medium-q_0, 11 for high-q_0 high-β, and 8 for high-q_0 medium-β equilibria. Two examples of the TAE mode structure are shown in Figure 2. The poloidal harmonics for each mode have poloidal mode numbers according to this notations: curve 'A' corresponds to $m = -1$, 'B' - $m = 0$, 'C' - $m = 1$ and so on, except 'Q', which denotes q profile.

STABILITY STUDY

Our analysis of TAE stability in NSTX is perturbative with eigenmode structure calculated by the ideal MHD code NOVA [5] and with drive and damping calculated by the postprocessor code NOVA-K. NOVA-K code was recently improved[6] to analyse the stability of Alfvén modes with arbitrary particle orbit width in general tokamak geometry. Trapped electron collisional damping is modified and includes now not only trapped electron interaction with parallel electric field[10], but electron compression effect as well. TAE drive is induced by the pressure gradient of NBI ions, which are injected tangentially to the major radius with beam width roughly equal to the half of the minor radius. The distribution function of fast ions needs to be calculated separately and is beyond the scope of this work, so that we assume the distribution function of fast ions to be slowing down in velocity with only copassing particles, and with gaussian distribution in pitch angle $\lambda = \mu B_0/E$, which is peaked at $\lambda = 0.3$ and has width $\Delta\lambda = 0.5$. Fast particle radial pressure profile is given by TRANSP for low- and medium-q_0 equilibriums and is $P_b(\psi) = P_{b0}\,(1 - \psi^{1.33})^{3.4}$ for high-q_0. Table 1 summarizes the results of the stability study. It shows the values of fast particle betas at the center, number of found stable or unstable eigenmodes for a given equilibrium, and the lowest found critical fast particle

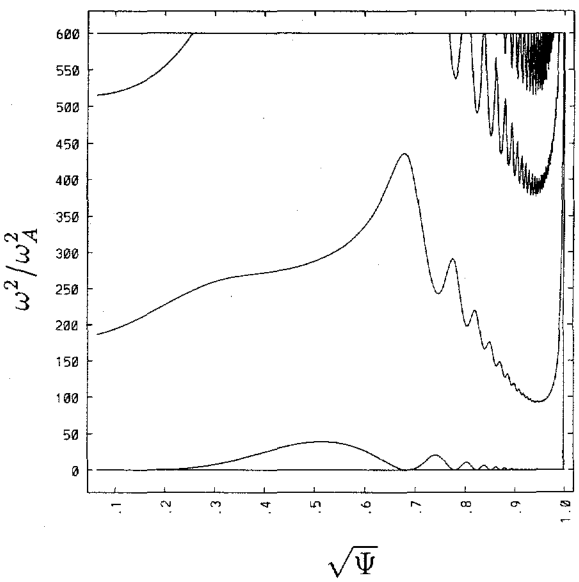

Figure 1: Alfvén continuum gap in NSTX plasma for $n = 3$ at high-q_0, high-β.

equilibrium	$\langle\beta\rangle$, %	$\beta_b(0)$, %	stable	unstable	strong drive $\gamma/\omega_A > 30\%$	lowest $\beta_{bcrit}(0)$, %
low-q_0	10	63	6	0	0	90
medium-q_0	10	11	19	3	0	9
high-q_0	15	> 22	6	5	6	0 (1)
high-q_0	8	> 10	5	3	2	0 (15)

Table 1: TAE stability analysis statistics and lowest fast ion critical beta.

beta when the mode can be unstable. In NSTX some TAEs have very strong drive, which is as high as $\gamma/\omega > 30\%$ and makes our perturbative approach unapplicable, that is the eigenmode structure and the eigenfrequency can be modified as compared to the MHD solution by fast particles during the mode nonlinear evolution. Other important result of our calculations is that NOVA-K predicts some unstable modes even without the fast particles, but at the same plasma parameters. The drive is coming from the tail of the Maxwellian plasma ions, which at energies $\mathcal{E} \simeq 6keV$ have the velocity close to the Alfvén velocity. For such case ($n = 5$) the value of the critical beta of fast ions is zero as shown in the table, where in the paranthesis the lowest beta is shown for the modes with damping and $n \leq 3$. The dominant damping mechanism is the ion Landau damping.

TAES EFFECTS ON FAST IONS

The guiding orbit code ORBIT[8] is used to calculate the efect of TAEs on the fast particle confinement in NSTX. Because of strong poloidal harmonic coupling each eigenmode has

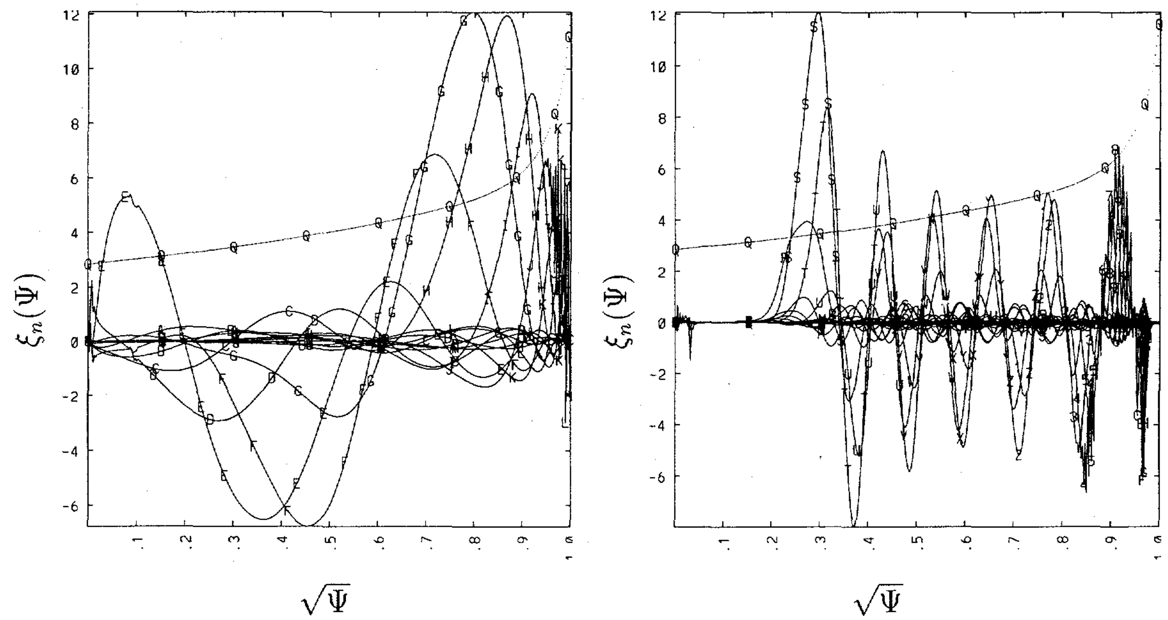

Figure 2: TAE mode structure for high-q_0 high beta NSTX plasma at $n = 1$ and $n = 5$.

to be represented by many harmonics, which is time consuming procedure for particle codes such as ORBIT. Thus in a case of single mode analysis we consider only $n = 1$ TAEs with the highest drive for each equilibrium. For the analysis of the effects of two TAEs we choose $n = 1$ and $n = 3$. NOVA-K is capable of predicting TAE's amplitude using the quasilinear theory[3][7], and can be used to evaluate the TAE amplitude in NSTX plasma. As there are a lot of uncertainties in plasma parameters we used only the trend in the parametric dependence of the eigenmode amplitude, which gives us typicallly for the amplitude at least an order magnitude higher value in NSTX than in TFTR at the same growth rate to damping rate ratio. This is due to higher "effective" collisionality in NSTX. Based on such scaling we fixed the TAE amplitude as the same value for all eigenmodes used in calculations $\tilde{B}_\theta/B = 10^{-3}$. Table 3 shows the results of ORBIT calculation of beam ion loss fraction for low $q_0 = 0.4$, $\langle\beta\rangle = 10\%$ and high $q_0 = 2.8$, $\langle\beta\rangle = 15\%$ equilibria. Shown are total losses when either no mode is present and the losses mostly happen during the first particle or one or two modes are included. The losses with no mode present are greater than those calculated by the guiding center code with FLR in TRANSP, where for the low-q0 equilibrium only about 10% loss is computed. We are investigating the difference in these results. In tokamaks at such TAE amplitudes

——	low-q_0	——		——	high-q_0	——
losses,%→	prompt	$n=1$ TAE		prompt	$n=1$	$n=1$ & $n=3$
no FLR	9	11		1	2	no data
with FLR	29	31		24	30	35

Table 3: Particle losses as simulated by ORBIT in low- and high-q_0 equilibria

resonances usually overlaps and produce significant particle losses[11]. In NSTX dispite the large beam ion FLR magnetic well near the center and strong edge poloidal magnetic field help to confine particle at high beta, so that TAEs do not produce large additional losses.

SUMMARY

A broad spectrum of TAEs may be unstable in NSTX. TAEs are found having global radial structure. Alfvén continuum gap exist even at high beta plasma, when TAE modes are present. TAEs may have strong drive $\gamma/\omega > 30\%$, which requires developing of nonperturbative codes for more robust calculations. Single and two mode calculations predict highest beam ion losses totaling in high beta high-q_0 plasmas $\sim 30\%$ of the NBI ion population with FLR effects included, where most of the losses are prompt losses (24%). Improved confinement (vs typical tokamak plasmas) is observed in high beta plasmas because of the presence of the magnetic field well and strong poloidal field at the edge. The results from START experiments[2] need to be analysed to provide the understanding of TAEs drive and damping in ST.

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