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by

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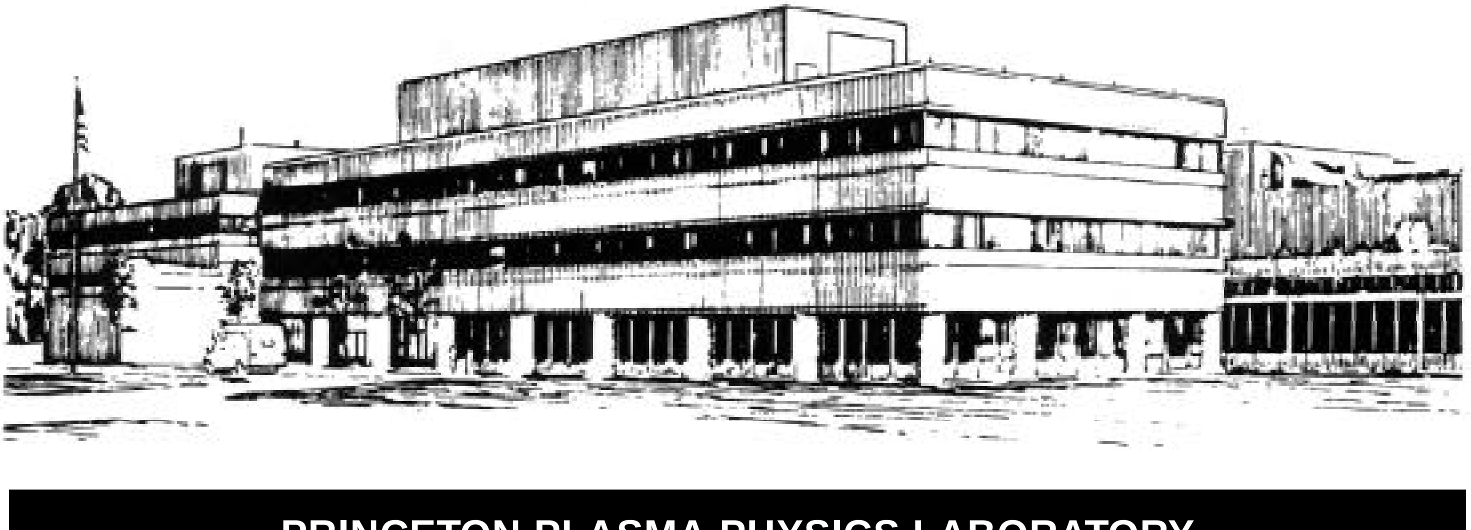

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Fast Particle Effects on the Internal Kink, Fishbone and Alfvén Modes.[†]

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Abstract. The issues of linear stability of low frequency perturbative and nonperturbative modes in advanced tokamak regimes are addressed based on recent developments in theory, computational methods, and progress in experiments. Perturbative codes NOVA and ORBIT are used to calculate the effects of TAEs on fast particle population in spherical tokamak NSTX. Nonperturbative analysis of chirping frequency modes in experiments on TFTR and JT-60U is presented using the kinetic code HINST, which identified such modes as a separate branch of Alfvén modes - resonance TAE (R-TAE). Internal kink mode stability in the presence of fast particles is studied using the NOVA code and hybrid kinetic-MHD nonlinear code M3D.

1. Introduction

Of major importance to a DT burning plasma is its ability to confine charged fusion products before they are thermalized. Such collective phenomena as internal kink modes, fishbones and Alfvén modes can possibly lead to expulsion of fast fusion products, degrade ignition margin and produce localized heating on plasma facing components. Hence, the requirements for the stability of such low frequency modes in the presence of fast particles are to be considered as a critical issue when building a reactor. New concepts, such as spherical torus (ST), ignitor tokamak FIRE, *etc.* emerged recently in an attempt to lower the cost of a tokamak reactor, but such concepts still need to satisfy the requirements for the stability of low frequency modes, driven by the pressure gradient of fast particles.

Existing numerical codes often can not satisfactory resolve mode structure and frequency of fast particle driven instabilities when the drive is large. In this report we present numerical tools available for the analysis of wide range of plasma instabilities including the nonperturbative ones. The issues of linear stability in advanced tokamak regimes is addressed based on recent developments in theory and progress in experiments.

2. Perturbative TAE Analysis in NSTX

Confinement of NBI ions used for plasma heating in ST, is one of the main concerns. Since the confinement of NBI ions can be strongly effected by Alfvén modes we address both issues of stability and ion confinement. Toroidal Alfvén Eigenmodes (TAE) [1] were already observed in START tokamak [2]. We analyze four model NSTX equilibria. The first one has a low central safety factor $q_0 = 0.4$, and $q_{edge} = 15$, which corresponds to the time-dependent analysis code (TRANSP) [3] run $\#11112P60$ with $\langle\beta\rangle \equiv 8\pi\langle p\rangle / \langle B^2\rangle = 10\%$. The second equilibrium has medium $q_0 = 0.7$, $q_{edge} = 16$ with $\langle\beta\rangle = 10\%$. The third and fourth equilibria have high $q_0 = 2.8$, $q_{edge} = 12$ with high beta $\langle\beta\rangle = 15\%$ and medium beta $\langle\beta\rangle = 8\%$, respectively. Pressure and density profiles are 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

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cases, while for high-q_0 case we use $P(\psi) = P(0)\,(1-\psi^{1.8})^2$, $n_e(\psi) = n_e(0)\,(1-\psi^{10})^{0.12}$, where ψ is the poloidal magnetic flux. The vacuum magnetic field is $B_0 = 0.3T$. Density and safety factor profiles are flat near the plasma center, creating an aligned gap along the minor radius. Calculations show that the Alfvén continuum gap is large, due to the effect of strong toroidal coupling and does not close at high beta $\beta \simeq 1$. For each toroidal mode number n we found several TAE modes. 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. Figure 1illustrates the gap structure, where the frequency of the continuum is shown as normalized to the central Alfvén frequency $\omega_A = v_{A0}/q_0R_0$, v_{A0}. High pressure leaves TAE gap open, allowing for global TAE to exist.

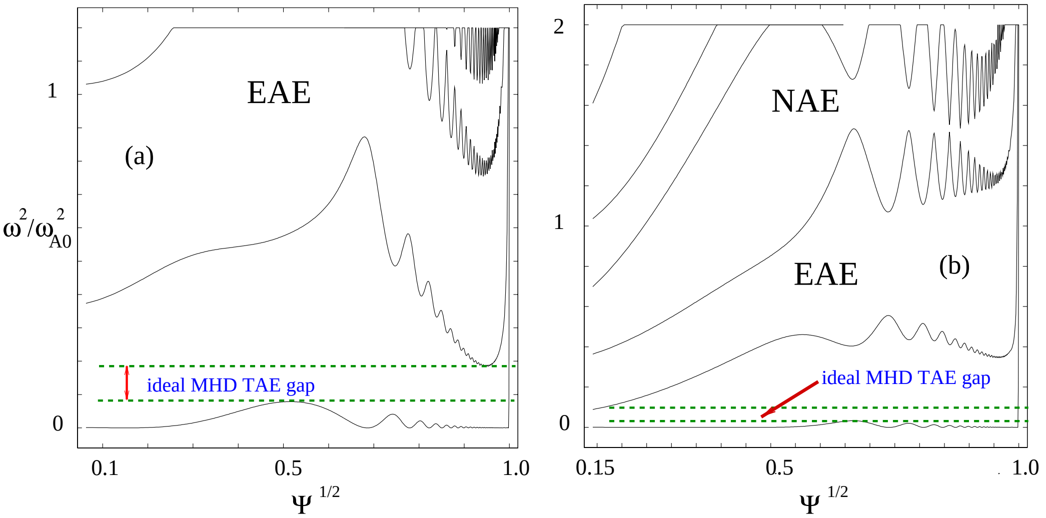

FIG. 1. Alfvén continuum gaps in NSTX plasma for $n = 3$ in medium-q_0 equilibrium with low ($<\beta>= 10\%$) and high ($<\beta>= 33\%$) plasma beta.

Calculations predict the broad TAE structure (see Ref. [4]for details).

Our analysis of TAE stability in NSTX is perturbative with eigenmode structure calculated by the ideal MHD code NOVA [5]. The NOVA-K code was recently improved [6] to analyze the stability of Alfvén modes with arbitrary particle orbit width. NBI ions are injected tangentially to the major radius. We assume the distribution function of NBI ions to be slowing down with a 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 $P_b(\psi) = P_{b0}\,(1-\psi^{1.33})^{3.4}$ for high-q_0. Following table shows fast particle betas at the center, the number of stable and unstable eigenmodes for a given equilibrium, and the lowest critical fast particle beta when a mode can be unstable. Linear perturbative calculations predict strong drive for TAEs, which may at $\gamma/\omega > 30\%$ makes our perturbative approach inaccurate. NOVA-K predicts unstable modes with $n > 3$, even without fast particles. The drive occurs because $\omega < \omega_{*i}$ and originates from the tail of the Maxwellian background ions, which at energies $\mathcal{E} \simeq 6keV$ have a velocity close to the Alfvén velocity. For such cases ($n = 5$) the critical beta of fast ions is zero. The parenthesis shows the lowest critical beam beta when thermal ions contribute only to the damping, i.e. $n \leq 3$.

equilibrium	$\langle\beta\rangle$, %	$\beta_b(0)$, %	# of stable modes	# of unstable modes	# of modes with $\gamma/\omega_A > 30\%$	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)

2.2. TAEs Effects on Fast Ions in NSTX

The guiding center orbit code ORBIT [7] is used to calculate the effect of TAEs on fast particle confinement in NSTX. We consider $n = 1$ TAE with the highest drive for each equilibrium. For the analysis of multiple TAEs, we choose $n = 1$ and $n = 3$. NOVA-K can predict TAE amplitude using theory [6] [8]. Based on NOVA-K calculations, we choose the TAE amplitude to have the same value for all eigenmodes with $\tilde{B}_\theta/B = 10^{-3}$. Following table 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 prompt losses which occur when no mode is present. Also shown are total fast ion losses when one or two modes are included. ORBIT code followed 1000 particles until they are thermalized. In tokamaks at such TAE amplitudes resonances overlap and produce significant particle loss [9]. In NSTX the magnetic well near the center and strong edge poloidal magnetic field help to confine particles at high beta. If a particle comes closer than Larmor radius ρ_b to the last flux surface it is considered lost, which may overestimate the losses.

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

3. Nonperturbative Alfvén mode study using HINST code

With large fast particle beta in tokamaks, modes with a time evolving frequency within the Alfvén frequency range are often observed. Modes with gradually evolving frequency on a time scale comparable with the plasma parameters evolution were called Beta-induced Alfvén Eigenmodes (BAE) in Ref. [10] observed in DIII-D at General Atomics. Gradually chirping modes (called "chirping" modes) were also reported later from TFTR [11] and JT-60U [12], where losses were seen during the instabilities. Our goal is to analyze such modes here using nonperturbative code HINST.

3.3. Nonperturbative ICRH-driven Gradually Chirping Modes in TFTR

During H minority ICRH in TFTR experiments, Alfvén frequency modes down chirp on a time scale of $100msec$ near the plasma core, as illustrated in Figure 4(a) (see [11] for details). First, the reflectometer picks up the signal at $r/a \simeq 0.2$, and then Mirnov coils start to measure the magnetic field edge perturbations, which implies the perturbation outward shift accompanied by the down-chirp of the frequency. H minority losses were seen at the plasma edge. After the gradually chirping mode starts, other types of Alfvén mode activity can be observed with only slightly evolving frequency, which are ideal TAEs. Gradually chirping modes are similar to ones observed in JT-60U experiments [13].

TRANSP has been applied for TFTR shot #74329. Basic plasma parameters for the time $t = 3.93sec$ were major radius $R_0 = 2.64m$, minor radius $a = 0.95m$, central plasma beta and density were $\beta_{pc}(0) = 1.1\%$ and $n(0) = 3.6 \times 10^{13} cm^{13}$, fast particle central beta $\beta_H(0) = 5.8\%$. NOVA predicts a radially closed toroidal Alfvén gap for this case. NOVA predicts the solution for low plasma central beta as a Core Localized Mode (CLM), but fails to resolve mode for central plasma beta $\beta(0) > \beta_{cr}(0) = 2.2\%$ because of interaction of core localized TAE solutions with the lower continuum. Obtained $\beta_{cr}(0)$ is much less than the predicted central total plasma beta by TRANSP $\beta(0) = \beta_{pc}(0) + \beta_H(0) = 6.9\%$.

New types of TAE branches are expected to exist in such plasma conditions and are known as RTAE [14] (or EPM [15]). RTAE can exist even inside the Alfvén continuum if the fast particle drive is strong enough to overcome the radiative continuum damping. At given plasma parameters near the plasma center with low shear, we can use only the local

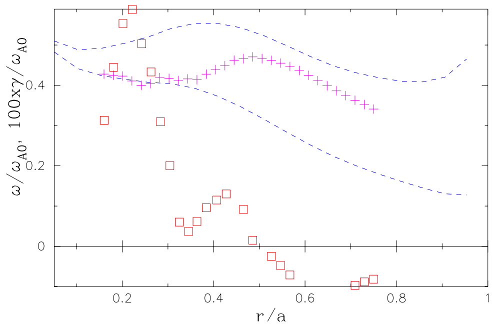

FIG. 2. RTAE frequency (shown as plus signs) and the growth rate (shown as open boxes) versus minor radius. Toroidal gap envelope is dashed lines.

version of HINST, which produces the mode frequency, the growth rate and the one-dimensional ($1D$) mode structure in the ballooning variables. The global HINST $2D$ solution requires radial localization of the mode and high toroidal mode number n [16]. HINST uses $s-\alpha$ model for the plasma equilibrium [17]. Since RTAEs have ballooning structure similar to TAEs, local equilibrium can be approximated as isotropic. We found RTAE solutions using the HINST code with a fast particle distribution function taken as Maxwellian in velocity space and all particles assumed trapped with their banana tip at the plasma center, which correspond to the on-axes ICRH heating.

The temperature of H minority ions was taken to be $300keV$. The results are shown in Figure 2 for $n=7$. It can be shown that the frequency of the solution near the minor radius with the strongest growth rate, i.e. at $r/a=0.2$, is below the lower gap boundary. At zero fast particle pressure the RTAE frequency goes even lower into the continuum and experiences stronger damping. To demonstrate the mode frequency chirping during the evolution of the q-profile between the sawteeth in ICRH TFTR discharges, we use a local version of HINST for different mode numbers $n=6,7,8$. Fig.3 presents the radial dependence of the RTAE mode frequencies. We assume that RTAE has the same location as core localized TAE, which is given by the minor radius at $q(r/a)=q_{RTAE}=q_{TAE}=(m-1/2)/n$. Thus $x_{RTAE}\equiv r/a=q^{-1}(q_{RTAE})$, where q^{-1} means the inverse function of q. A higher toroidal mode number is further from the plasma center at given $q_0<1$ and monotonic q-profile. Finally, we superimpose the RTAE frequency versus minor radius dependence with the dependence $x_{RTAE}=q^{-1}(q_{RTAE})$ and calculate frequency time dependence assuming $q_0(t)$ is linear [4].

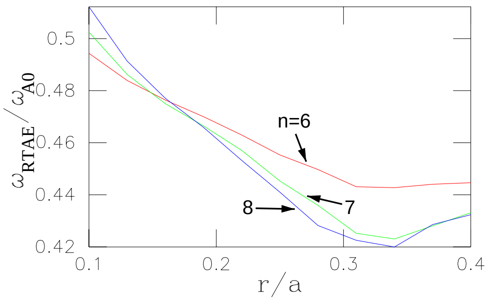

FIG. 3. RTAE frequency radial dependence for different toroidal mode numbers $n=6,7,8$.

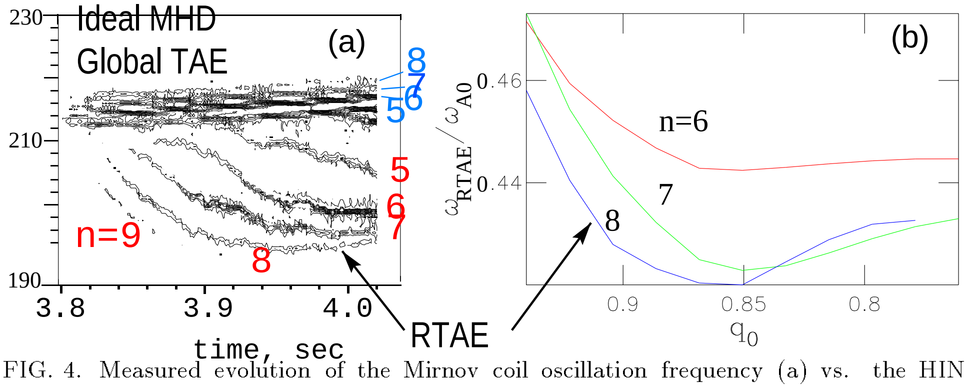

FIG. 4. Measured evolution of the Mirnov coil oscillation frequency (a) vs. the HINST predicted RTAE frequency "evolution" (b) expressed as a function of central safety factor q_0.

Figure 4 shows the comparison of the measured frequency and HINST calculated frequency evolution. Two dependencies are qualitatively similar and have the same toroidal mode number time sequence. The growth rate is of the order of $\gamma/\omega\simeq 2\%$ may justify our linear approach against the nonlinear chirping mechanisms. Such analysis can be done only with the nonperturbative codes such as HINST. It is not due to the presence of a large number of fast particles, which changes the background plasma dispersion and creates a new RTAE branch.

3.3. Negative NBI Excitation of Gradually Chirping Modes in JT-60U Experiments

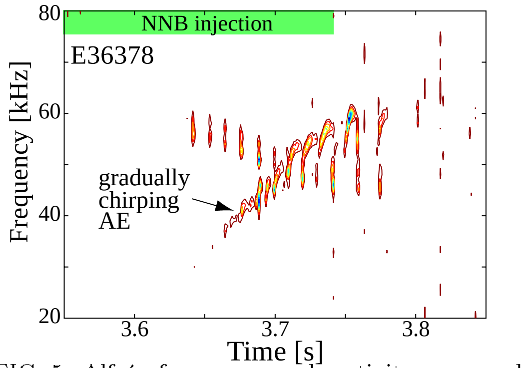

FIG. 5. Alfvén frequency mode activity measured by edge Mirnov coils in JT-60U NNBI injection experiments shot #36378.

In JT-60U the Negative-ion-based Neutral Beam Injection (NNBI) at ion energies $\mathcal{E}_{b0} \simeq 350keV$ [12] was applied tangentially into the plasma with a low toroidal magnetic field $B = 1.2T$, so that beam ions were super Alfvénic. Typically achieved fast particle central betas were comparable with the total plasma toroidal beta. Figure 5 presents results of these measurements reported in Ref. [18] for low-n oscillations. One can see two kinds of mode activity. In the first one, the mode starts at $t \simeq 3.65sec$ with initial frequency $f \simeq 30kHz$, and gradually chirps up within $\sim 200msec$ to $f \simeq 60kHz$ by the time $t = 3.75sec$. Such long chirping may be caused by the slow equilibrium evolution as was illustrated in Ref [4].

HINST code can analyze high-n modes and, thus, can provide rather qualitative results for this case when only low-n oscillations are observed. Here we again use a local version of HINST to model the mode frequency evolution in the linear theory due to the change in the plasma equilibrium. NNBI ion and plasma beta are provided by OFMC code modeling, while q-profile shown on Figure 6 is based on the MSE measurements. Total beam pressure is of the order of plasma beta $\beta_h(0) \sim \beta_p(0)$. The local shear is increased in the core region.

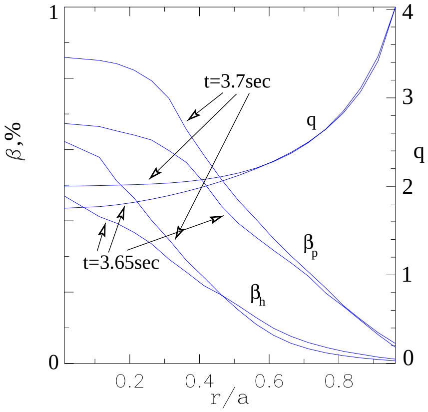

FIG. 6. NNBI injected beam ion and bulk plasma beta profiles and q-profiles shown at two time slices for JT-60U shot #36378: $t = 3.65sec$ and $t = 3.7sec$.

We found two different types of modes when the HINST code was applied for $n = 5$ at $t = 3.65sec$, i.e. when the gradually chirping mode was first observed. Figure 7 shows the HINST results as dependencies of eigenfrequencies and growth rates for both branches on the minor radius. Lower frequency mode is close to the kinetic ballooning mode (KBM) branch [19]. The KBM is stable without fast particles, as can be seen in Figure 8, which is calculated for the time slice $t = 3.65sec$. We will call this mode RTAE as it is transformed into the branch close to perturbative TAE if the total beta is increased, or if the mode location is shifted in radius (see left Fig.7). Higher frequency RTAE is closer to the TAE in frequency [see Figure 7(b)] and in mode structure [4]. The most unstable mode is the low frequency RTAE and thus is expected to be excited first.

We study the properties of low frequency RTAE at $r/a = 0.3$, where $\beta_h(r/a = 0.3) = 0.3\%$. Below, all the frequencies are normalized to the $\omega_{A0}(t = 3.65sec) = 0.81 \times 10^6 rad/sec$. RTAE frequency increases slightly when we change only fast particle pressure keeping the plasma core beta constant. On the other hand if the total pressure is changed and kept proportional to the fast particle pressure the frequency increases significantly. In Ref.

[4] fast particle beta was stronger, which resulted in stronger correlation with the RTAE frequency when only β_h was changed. Increase of the total pressure can model the build up of the plasma pressure during the beam injection. Changing magnetic shear does not change the frequency.

HINST results imply that RTAE frequency for $t = 3.65 sec$ will be $f = 32 kHz$ and $f = 41.6 kHz$ for $t = 3.7 sec$, which agrees well with the observations (Fig. 5). Other property of RTAE is that the lowest n number modes are the most unstable [Figure 8(right)], which agrees with experimental observation of the lowest n numbers $n = 1 - 2$.

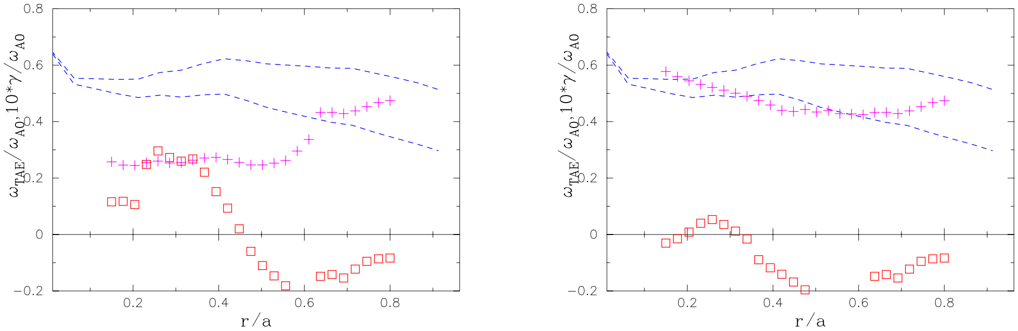

FIG. 7. HINST analysis of the start of gradual chirp $t = 3.65 sec$. Strongest driven low frequency RTAE (left) has drive maximum at $r/a \simeq 0.3$. High frequency RTAE (right) is less unstable.

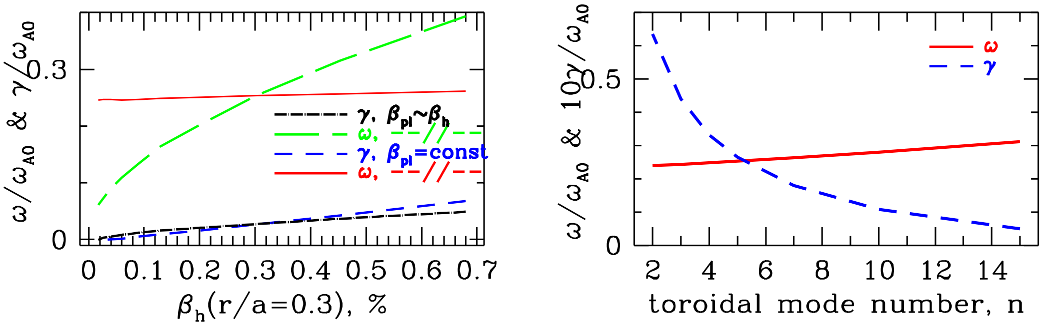

FIG. 8. Properties of RTAE as dependencies of its frequency and growth rate on fast beam ion and plasma beta (a) and toroidal mode number n (b).

4. Internal Kink Mode Stabilization by Fast Particles

To study the fast particle driven low frequency instabilities [6], [20] NOVA is being developed for the nonperturbative low-n analysis. NOVA-K being perturbative is also used to calculate full fast particle response to the internal kink modes. The outline of formulation is presented below.

To study the properties of the 1/1 internal kink mode stabilization by NBI ions we compute energy quadratic form, which includes hot particles [6] $\delta K = \delta W \equiv \delta W_{MHD} + \delta W_{kh}$, $\delta K = \omega^2 \int \rho \xi^2 d^3 r$, where δK is mode kinetic energy, ξ is plasma displacement, ρ is plasma mass, ω is mode complex frequency. The 1/1 mode structure is given by NOVA code without fast particles, but with total pressure including all species. Unlike the ideal MHD case, where $\delta K \sim \omega^2$, perturbative code NOVA-K makes use of the assumption that $\delta K \sim \omega$, which is based on the dependence of the inertial layer width proportional to ω^{-1}. This leads to the following dispersion relation [20]

$$-i\omega \left(1 + \frac{\omega_T^2}{\omega_s^2 - \omega^2}\right) = \gamma_{MHD} \left(1 + \frac{\gamma_h}{\gamma_{MHD}}\right), \quad \frac{\gamma_h}{\gamma_{MHD}} = \frac{\Re \delta W_{kh}}{\delta K}, \tag{1}$$

where $\omega_T^2 = 2\gamma_s P_c \kappa/\rho$, $\omega_s^2 = (1/2)\gamma_s \beta_c \omega_A$, κ - curvature, $\gamma_s = 5/3$, ρ is plasma mass, γ_{MHD} is the ideal kink mode growth rate without fast particles. One can see that the real part of the fast particle contribution to the potential energy $\Re\delta W_{kh}$ can change the growth rate and produce stabilization. Fast particle contribution is computed in NOVA-K and nonperturbative NOVA-2 code according to the following formula [6], which includes particle finite orbit width (FOW)

$$\delta W_{kh} = -(2\pi)^2 e_\alpha c \int dP_\varphi d\mu d\mathcal{E} \tau_b \sum_{m,m',l} \frac{X^*_{m,l}(\omega - \omega_*) X_{m',l}}{\omega - \overline{\omega_d}} \frac{\partial F_h}{\partial \mathcal{E}}, \qquad (2)$$

where the integration is performed over the particle phase space, τ_b is the particle bounce time, $X_{m,l}$ gives wave - particle interaction power exchange, F_h is the fast particle equilibrium distribution function, $\omega_* = -i\frac{\partial F/\partial P_\varphi}{\partial F/\partial \mathcal{E}} \frac{\partial}{\partial \varphi}$, and ω_d is particle toroidal drift frequency. One needs $\omega < \omega_d$ for the stabilization to occur. Since the 1/1 mode frequency is associated with plasma diamagnetic frequency ω_* and $\omega_d \sim \mathcal{E}$, particles should be energetic enough $\omega_* < \omega_d$ to provide the stabilization. The expression Eq.(2) can be modified to account for the plasma rotation on fast particle contribution by simply substituting the mode frequency $\omega \to \omega - \Omega_E(\psi)$, where $\Omega_E(\psi)$ is plasma toroidal rotation as a function of poloidal flux. This can be shown more rigorously [22]. The effect of the rotation coming from the denominator is dominant.

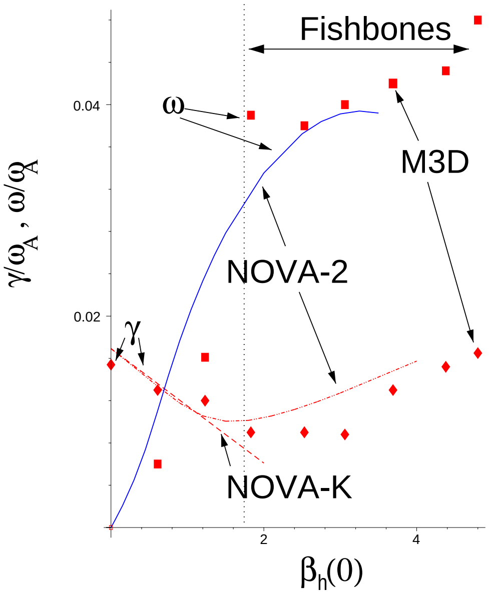

FIG. 9. Codes benchmark for ideal MHD kink mode.

We have performed the benchmark of NOVA-K with its previous nonperturbative version NOVA-2 and with M3D codes for one particular case with circular plasma cross section and the following plasma parameters: major radius $R_0 = 2.62m$, minor radius $a = 0.95m$, plasma central beta $\beta_{pl}(0) = 5\%$, fixed total beta on Fig.9 ($\beta_{pl} + \beta_h = const$), and toroidal magnetic field $B = 4.45T$. Deuterium hot slowing down ions with cutoff velocity $v_h = 10^9 cm/sec$, ratio to central Alfvén velocity $v_h/v_{A0} = 1$, major radius to particle Larmor radius ratio $R/\rho_h = 55.6$. The NOVA-2 code [20] calculates the mode structure non-perturbatively with fast particles included in the quadratic form. In the benchmark we also use M3D [21], which is a non-linear code, with fast particles included. With the zero beta of fast particles the growth rate of ideal kink mode is reproduced by three codes. If we increase fast particle beta it is stabilized. Linear stabilization phase of $m/n = 1/1$ kink mode agrees well for three codes. When β_h is increased further, the mode frequency becomes comparable with the particle precession frequency. At this point the mode is more destabilized by fast particles and is transformed into the fishbone branch. Since fishbone branch is nonperturbative, NOVA-K can not reproduced it and only M3D and NOVA-2 can be used. Fishbone frequency is of order of particle toroidal precession drift frequency $\omega_{dr\varphi}/\omega_{A0} = 0.49$, where $\omega_{A0} = v_{A0}/R$. Application of NOVA-K to JET and TFTR experiments is presented in Ref. [23].

Used here M3D code can be applied to study the nonlinear effects of ideal kink and TAE modes on fast particles. One of such study suggests, as will be reported elsewhere, that the fishbone saturates due to particle nonlinearity for *small* linear growth rates. However the MHD nonlinearity plays a significant role at *large* linear growth rates.

5. Summary

Numerical framework to study both perturbative and non-perturbative instabilities driven by fast particles is presented.

Many TAEs may be unstable in NSTX. TAEs are found to have a global radial structure. The Alfvén continuum gap exists even at high plasma beta, with TAE modes present. Single- and two-mode calculations predict the highest beam ion loss in high beta high-q_0 plasmas $\sim 35\%$ of the NBI ion population with FLR effects included, where most of the losses are prompt losses (24%). Good fast ion confinement is observed in high beta plasmas because of the presence of the magnetic well and strong poloidal field at the edge.

HINST code has been used to model experimental observations of the gradually chirping modes. Agreement is achieved for the modeling of gradually chirping modes in TFTR, where a slow q-profile evolution is shown to produce the frequency chirp. Pressure build-up is suggested to be responsible for the gradually chirping mode observed in JT-60U experiments, in which HINST shows that the KBM branch destabilized by NNBI ions can be transform into the RTAE on the time scale of the equilibrium evolution. This further unveils the possible application of the theory to the RTAE instability in the reactor conditions when strong pressure gradient region is accompanied by the low shear.

Numerical tool to study nonperturbative excitation of ideal kink modes and their transition to the fishbone branch is presented. Both perturbative and nonperturbative codes agree well with each other and with the fully nonlinear code M3D, which was run in linear regime.

In the near future a more comprehensive code which includes a nonperturbative treatment of fast particle contribution is needed for low-n mode analysis and for more accurate modeling of the linear and nonlinear interaction. Such code NOVA-2 is being developed.

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