Resonant kinetic ballooning modes in burning plasma[1]

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Due to the high energy of fusion products in burning plasmas, alpha particles will be superalfvenic with the ratio of their birth velocity to the characteristic Alfvén velocity such as $v_{\alpha 0}/v_A = 1.8$ in planned ITER experiments. This may result in various branches of Alfvén instabilities such as predicted TAE (toroidicity induced Alfvén eigenmode [1]) instability in regular shear plasma [2, 3]. This work presents the study of the instability of the kinetic ballooning mode (KBM) branch, driven by the radial pressure gradient of fusion alphas in a regular shear ITER plasma. Due to their potential to induce radial fast ion transport and possibly heat flux onto the first wall, the instabilities driven by the radial pressure gradient can limit plasma performance and are very important for ITER.

Typically, resonant interaction of KBMs (resonant KBMs or RKBMs) with energetic particles results in an instability with a large growth rate and a high toroidal mode number. The RKBM growth rate strongly depends on the details of the alpha particle population distribution in the phase space. The mode frequency is close to the thermal ion drift frequency calculated with the background ion pressure gradient, ω_{pi}. In present day experiments, modes in that frequency range have been observed in DIII-D [4] and were called beta-induced Alfvén eigenmodes (BAEs). Recent analysis indicates that BAEs can be identified as RKBMs [5]. Such modes fall into a category of energetic particle modes [6] or resonant modes [7].

In this work, we will perform linear nonperturbative fully kinetic stability analysis with the help of a local ballooning code HINST (high-n stability code [8]). HINST solves a set of three equations (for details see Ref.[9]): the vorticity equation, the quasi-neutrality condition, and the perpendicular Ampere's law for the perturbed parallel component of the magnetic field. It is able to reproduce both the TAE and KBM branches with a drive from fast particles included non-perturbatively. Calculations of mode drive and damping include bulk plasma and fast particle Finite Larmor radius (FLR) effects. Radiative damping supported by trapped electron collisional effects and ion Landau damping are also incorporated. Even though HINST robustly finds solutions with high toroidal numbers that have radially localized mode structures, it can be used for medium to low modes in the local version [5], i.e. without resolving the two dimensional (2-D) mode structure. HINST employs a shooting technique to find the mode frequency, growth rate and one dimensional (1-D) mode structure in ballooning coordinates. Note that the global HINST 2-D solution requires radial localization of the mode and high toroidal mode numbers. HINST uses numerical plasma equilibrium [10], which assumes an isotropic plasma pressure.

HINST Modeling of KBM Instability

In this section we numerically analyze the stability of KBM modes in an ITER plasma with a regular shear safety factor profile. We make use of the results of the TRANSP analysis code

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[11], where appropriate ITER plasma parameters were obtained. In our model only alphas are included with alpha particle distribution function assumed to be isotropic and slowing down. The frequency of the resonant KBMs, $\omega \simeq \omega_{*pi}$, is close to the precessional frequency of the alphas, $\omega_{d\alpha}$, so that the drive is coming primarily from trapped ions. For this reason, beam ions injected tangentially are not expected to affect the KBMs and are ignored in the kinetic response. However, beam ion beta contributes to the total plasma beta as a background specie.

The plasma profiles for the baseline scenario are shown in Figure 1 as functions of the minor radius defined through the normalized toroidal field flux $\rho = \sqrt{\Phi/\Phi_0}$. Other plasma parameters used were: a major plasma radius of the geometrical center of $R_0 = 6.2m$, a minor radius of the last magnetic surface of $a = 2m$, a deuterium negative Neutral Beam Injection (NBI) power $P_{NBI} = 33MW$ at an energy $E_{b0} = 1MeV$, a vacuum magnetic field at the geometrical axis of $B_0 = 5T$, a total central beta value of $\beta_0 = 6.6\%$, poloidal cross section ellipticity and triangularity of $\kappa = 1.85$ and $\delta = 0.49$, and ion and electron temperatures in the center of $T_{i0} = 19.5keV$ and $T_{e0} = 23.5keV$, respectively. Note that for alphas $\rho_{*\alpha} = \rho_{\alpha 0}/a \simeq 40$, which means that modes with high n's (high $k_\perp$) can efficiently interact with the alpha population without being stabilized by fast ion FLR, such as high-n TAEs [3].

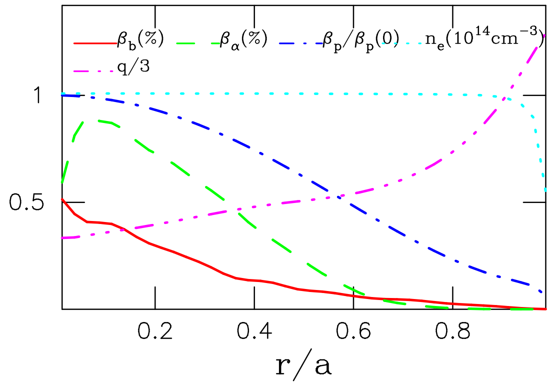

FIG. 1: *Plasma profile for ITER normal shear scenario used in HINST simulations. Shown are profiles of beam beta, β_b, fusion product alpha particle beta, β_α, normalized plasma beta $\beta_p/\beta_p(0)$, electron density, n_e, and safety scaled by factor $1/3$, $q/3$.*

HINST shows that ideal ballooning mode (IBM) is unstable for the baseline plasma case within minor radius domain $0.57 < \rho < 0.8$ (strongest pressure radial gradient) with zero triangularity and $\kappa = 1$. Increasing ellipticity to $\kappa = 1,2$ stabilizes IBM. Without alpha particles, KBMs are stabilized by the trapped electron collisional damping, but further study is required. Trapped alphas provide the drive for KBMs due to precessional frequency resonance. The mode structure of the RKBM solution as a function of the ballooning poloidal angle is shown in Figure 2. As expected for the ballooning mode, the structure is localized at $\eta = 0$.

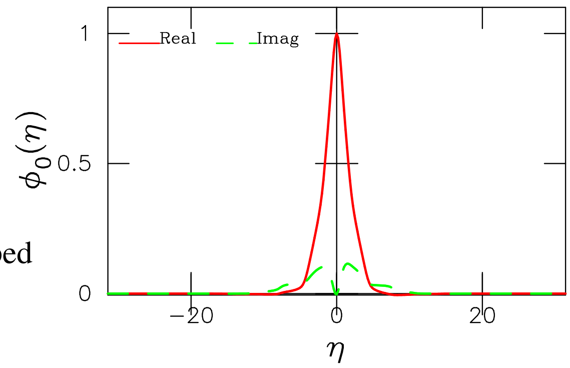

FIG. 2: *Electrostatic potential for the baseline scenario RKBM solution at $n = 22$ and* $\rho = 0.48$.

Toroidal mode number dependence of the RKBM frequency and the growth rate are shown in Figure 3(a). All the quantities are normalized to the central Alfvén frequency, which in this case is $\omega_{A0} = 1.1 \times 10^6 (rad/sec)$. The characteristic frequency of RKBMs is then $\sim 17kHz$, which is about one third of the TAE gap frequency. The mode does not exist below $n = 17$

and is stabilized by thermal ion FLR at $n > 23$. The resonance condition in the phase space, $\omega_{d\alpha res} \simeq \omega_{*pi}$, is narrow due to these frequencies opposite radial variations. We also note that the resonance energy for trapped ions is close to $1MeV$. It is also seen from that figure that the mode frequency follows the thermal ion drift frequency. Radial dependence of the mode frequency and growth rates is shown in Figure 3(b). The location of the unstable region of the RKBMs coincides with the maximum of the pressure gradient of the alpha particles. Because of their localization, RKBMs are not expected to have a strong effect on energetic ion transport. However, local flattening of trapped alphas can be expected.

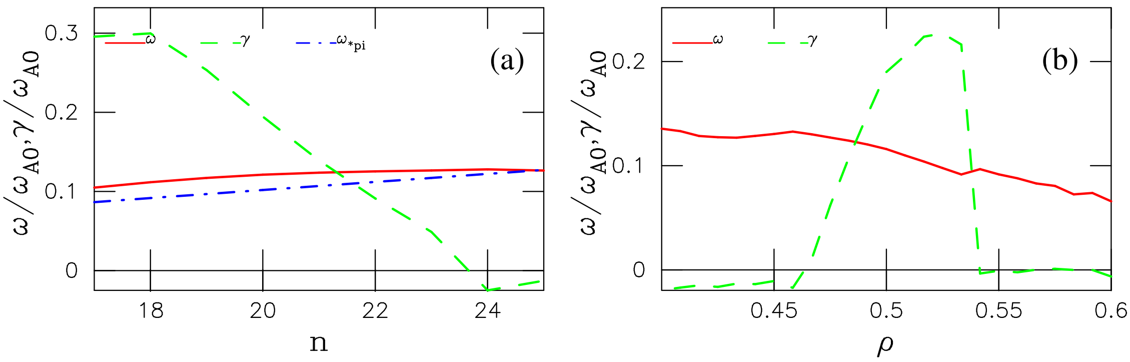

FIG. 3: *RKBM frequency and growth rates dependence on toroidal mode number (figure (a),* $\rho = 0.48$*) and minor radius (figure (b),* $n = 22$*) for the baseline scenario.*

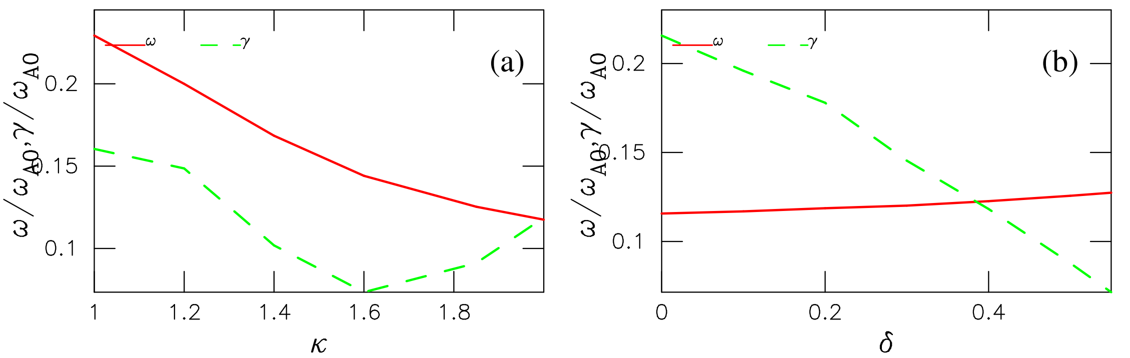

FIG. 4: *RKBM frequency and growth rate dependence on plasma cross section ellipticity (figure (a) at* $\delta = 0.49$*) and triangularity (figure (b) at* $\kappa = 1.85$*).*

As in the case of IBMs, the geometry effects are strongly stabilizing for RKBMs. This is seen from Figure 4 (a) and (b). The mode is not completely stabilized, but the growth rate is significantly reduced within a factor of two by increasing the ellipticity and the triangularity from 1 to 1.85 and from 0 to 0.5, respectively. In each study the rest of plasma parameters corresponded to the baseline case.

As calculations show, for the RKBMs to be unstable it is required that the central value of the alpha particle beta be above a threshold $\beta_{\alpha 0} > \beta_{\alpha crit} = 0.6\%$ as one can see from Figure 5. The RKBM instability growth rate strongly picks up above $\beta_{\alpha crit}$, which is within the proposed operational point for ITER.

Conclusions

With the nonperturbative fully kinetic code HINST, we have shown that in a proposed ITER normal shear plasma, a resonant KBM is expected to be driven unstable by fusion alpha particles.

The instability has a mode frequency close to the thermal ion drift frequency and is excited by trapped alphas via the drift precessional resonance. The RKBM unstable region spans within the minor radius $0.46 < \rho < 0.54$ and has high n's from $n = 17$ to $n = 23$. The ITER operating point is above the threshold of this instability, which is $\beta_{\alpha crit} = 0.6\%$. The poloidal cross section ellipticity and triangularity provide strong stabilizing effects. It is also found that the ideal ballooning modes are stable due to the geometrical effects, whereas nonresonant KBMs (i.e., in which the interaction with fast ions is ignored) are stabilized by the trapped electron collisional damping. Because of their localization, RKBMs are not expected to have a strong effect on energetic ion transport. However, local flattening of trapped alphas, as well as associated radial electric field and plasma rotation, can be expected.

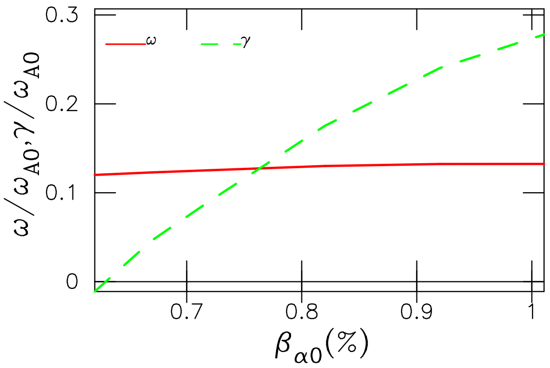

FIG. 5: *RKBM frequency and the growth rate for the baseline scenario and* $n = 22$ *and* $\rho = 0.48$.

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