Linear and Nonlinear Dynamics of Alfvén Eigenmodes in JET Plasmas

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ABSTRACT

The stability of Alfvén eigenmodes in JET is studied using a Hybrid Gyrokinetic MHD model which takes into account finite orbit effects, realistic plasma geometry and Alfvén waves fields including first order ion Larmor radius corrections. This analysis provides stability diagrams for global Alfvén eigenmodes in the presence of fusion products or energetic ions generated by auxiliary heating. The nonlinear evolution and saturation of the modes is studied using an Hamiltionian guiding center description of the particle motion in a perturbed magnetic field with a self consistent update of the amplitude and phase of the wave.

INTRODUCTION

The influence of energetic particles on the stability of Alfvén waves in the Joint European Torus (JET) is analysed using a three-step numerical procedure. First, the equilibria are reconstructed using the codes EFIT and HELENA. Secondly, linear properties of the toroidal Alfvén wave spectrum are determined by the MHD normal-mode code CASTOR (Complex Alfvén Spectrum in TORoidal geometry). The linear stability analysis includes the determination of the principal wave damping mechanisms, i.e. ion and electron Landau damping, radiative damping and collisional electron damping as well as the evaluation of the instability drive including effects due to large, non-standard (i.e potato) orbits characteristic of alpha particles and of radio-frequency-heated (RF) ions in the JET tokamak. Finally, the nonlinear mode evolution, including amplitude saturation and fast-particle redistribution/loss, is computed using the particle code FAC (Fast particle-Alfvén wave interaction Code).

JET discharges with a large fraction of RF and NBI generated ions are studied with distributions based on Fokker-Planck simulations using the codes PION (for RF ions) and PENCIL (for NBI ions). Possible scenarios for TAE excitation by alpha particles, as well as by NBI and/or RF-produced energetic ions, are studied in conditions relevant to JET DT experiments.

MODEL

Using the MHD equilibria reconstructed by EFIT and HELENA, the linear normal-mode analysis is performed by the spectral codes CSCAS and CASTOR. The linear MHD model (CASTOR-CR) includes first order finite ion Larmor radius effects and the perturbed parallel electric field. The CASTOR-CR code solves the linearized MHD equations with the parallel resistivity obtained from kinetic theory:

$$\eta \approx 4\pi i \omega \rho_s^2 \left(\frac{3}{4} + \frac{T_e}{T_i} (1 - i\delta_e) \right).$$

The electron dissipation includes collisional damping δ_e due to a finite longitudinal electric field and collisional curvature damping obtained from a tabulated solution of the bounce-averaged electron kinetic equation. ρ_s is the ion sound Larmor radius, T_i, T_e are the ion and electron temperatures and ω frequency of the perturbation. The contribution of energetic ions is included perturbatively. The CASTOR-K code computes the first order perturbation on the eigenvalue due to the resonant interaction between the wave and the energetic ion population using a gyro-kinetic model. The resonant Landau damping from thermal particles is included in the same fashion.

$$(\omega_r + i\omega_i)^2 K = \delta W_{MHD} + \delta W_{hot} \ , \ \frac{\gamma}{\omega} = \frac{\omega_i}{\omega_r} = \frac{Im[\delta W_{hot}]}{2\omega_r^2 K}$$

K representes the kinetic energy of the perturbation, δW_{MHD}, represents the MHD part and δW_{hot} represents the contribution from energetic ions to the eigenvalue. CASTOR-K utilises the linear eigenfunction obtained by CASTOR-CR and decomposes the hot particle energy functional into poloidal bounce harmonics and integrates the resonant contribution over the particle phase-space $dP_\phi dE d\mu$ [3],

$$\delta W_{hot} = -\frac{2\pi^2}{\Omega m^2} \sum_{\sigma} \int dP_\phi dE d\mu \sum_{p=-\infty}^{\infty} \frac{\partial F}{\partial E} \frac{\tau_b \mid Y_p \mid^2 (\omega - n_0 \omega_*)}{\omega + n_0 \omega_D + (n_0 q + p)\omega_b}, Y_p = \oint \frac{d\tau}{\tau_b} \overset{(1)}{L} e^{ip\omega_b \tau}.$$

$L^{(1)}$ represents the perturbed Lagrangian of the unperturbed particle motion, ω_D, ω_d the precessional drift and bounce particle frequencies. The nonlinear dynamics is studied using the FAC code. The nonlinear interaction of a discrete spectrum of low-β fluid modes with a hot particle source is described by a Hamiltonian guiding center scheme for the particle motion in the presence of a field perturbation with a self consistent differential update of the phase and the amplitude of the wave. The time evolution of the perturbed distribution function δf is described as an initial value problem by a set of markers (quasi-particles).

$$\frac{d}{dt}\delta f_{hot} = -\frac{d}{dt} f_{hot}{}^{0} - \nu \delta f_{hot}$$

ANALYSIS OF JET DISCHARGES IN THE PRESENCE OF ALPHA PARTICLES

Due to a combination of the mode structure and the finite orbit effects the most unstable modes in JET in the presence of alpha particles $E = 3.5\ MeV$ are KTAE modes with n=5 to 8. The analysis shows that alpha particles have a strong destabilising effect $\gamma/\omega \approx 2\langle\beta_\alpha\rangle$. But due to the alpha particle pressures possible in JET tritium experiments $\langle\beta_\alpha\rangle \le 10^{-3}$ and the various damping mechanisms, these modes are expected to be marginally stable as shown in figure 2. The nonlinear simulations show that when the KTAEs are found to be unstable the saturation amplitude scales as $\frac{\delta B}{B} \approx 0.5\left(\frac{\gamma}{\omega}\right)^2$ and therefore the saturation amplitude is small $\frac{\delta B}{B} \approx 10^{-5}$. For these amplitudes no significant anomalous alpha transport is expected. The computations are based on a typical JET high performance discharge with $n_e = 5 \times 10^{19} m^{-3}$, $B_0 = 3T$, $T_i \approx 10 \rightarrow 20 KeV$ and $T_e = 10 KeV$, using an alpha particle slowing down distribution. In the stability diagram the ratio between the alpha particle velocity and the Alfvén velocity on axis $\frac{V_\alpha}{V_A}$ is scanned by changing the plasma density.

INFLUENCE OF NBI AND RF HEATING

High performance JET discharges are characterized by a large auxiliary heating power in the form of NBI or/and RF. Due to the nature of the orbits of RF generated ions (trapped ions), it is more difficult to excite KTAE modes than TAE modes with RF heating. The interaction between TAE modes and RF is strongest when the RF resonant layer is localised at the low field side of the torus as shown in figure 4.

NBI injected ions have lower energy $E \le 140 KeV$ than RF produced ions $E \ge 500 KeV$ and are expected to destabilise only high-n (n>10) TAE and KTAEs at high densities. For low-n (n<10) modes the beams should have a stabilising effect. Detailed calculations including the radiative damping of high-n modes, the ion Landau damping at high densities and the destabilising effect of large beam power on high-n TAE and KTAE modes are required in order to determine the stability boundaries.

CONCLUSIONS

The hybrid Gyro-Kinetic-MHD model developed provides detailed description of the interaction of energetic ions with global plasma waves taking into account: realistic geometry, finite particle orbit width including large non-standard orbits, realistic wave fields including first order ion Larmor radius corrections and linear and nonlinear evolution. Applications of the model to JET high performance discharges show that due to orbits effects RF ions do not have a strong influence on the KTAE modes. On the another hand neutral beam generated ions can destabilzize only high-n (n>10) TAE and KTAE modes at high densities. Alpha particles will have a strong destabilising effect only on low-n KTAE's modes due to finite orbit effects. As a consequence of the small alpha particle pressure and the various sources of damping low-n modes should be marginally stable in the JET tritium experiments.

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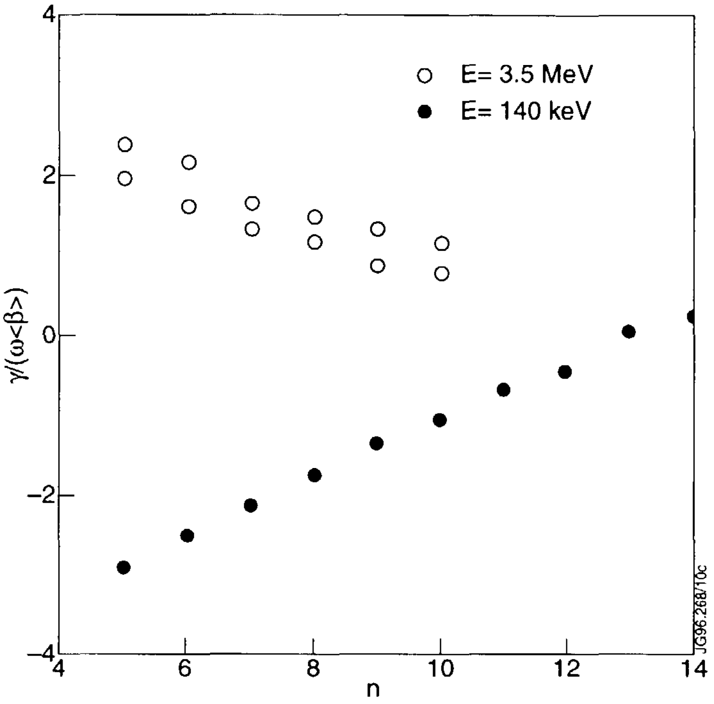

Figure 1 Drive due to a slowing down distribution of alpha particles and NBI generated ions for KTAE modes as a function of the toroidal mode number.

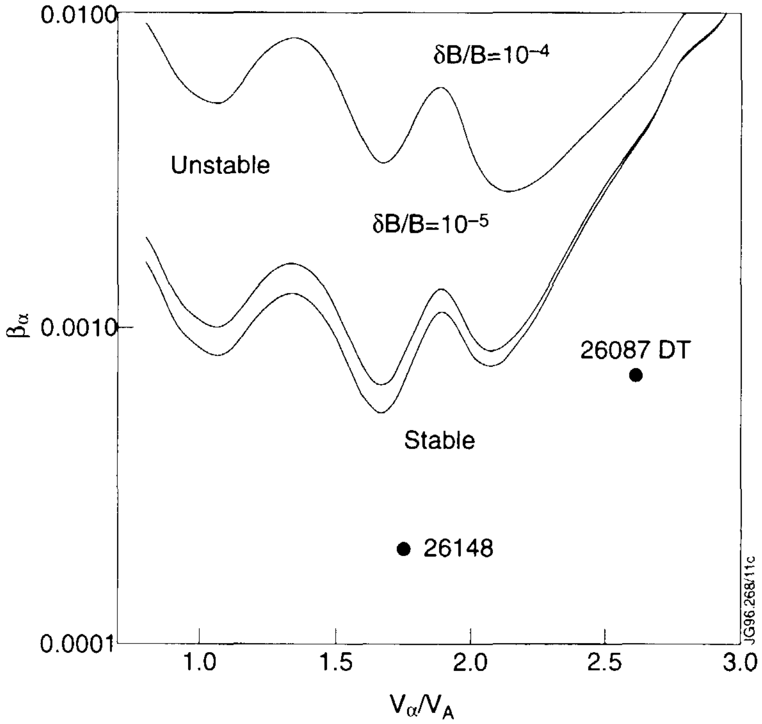

Figure 2 Stability diagram for KTAE modes in JET high performance discharges for 1) the preliminary tritium experiment PTE1 #26148 and 2) a future 50% tritium discharge based on #26087.

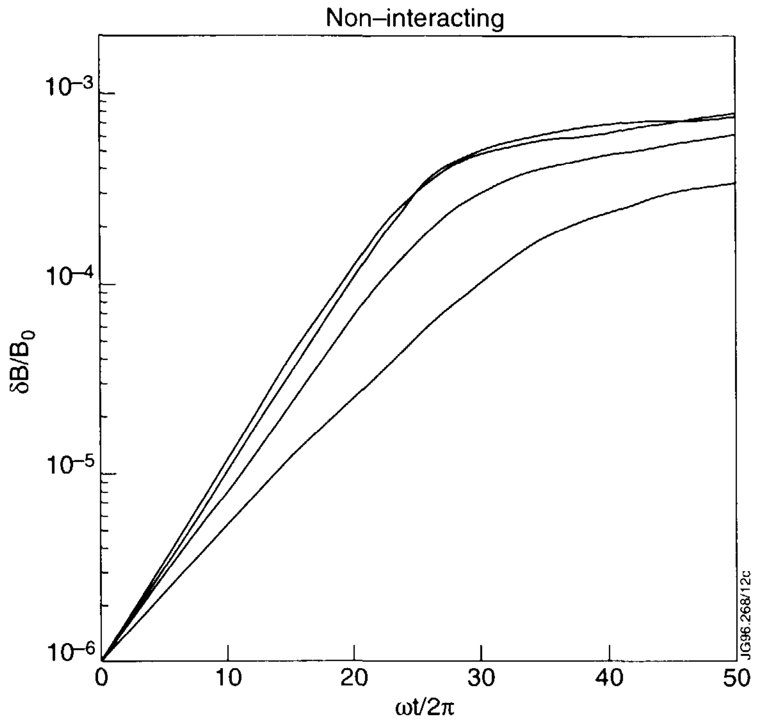

Figure 3 Nonlinear evolution of unstable KTAE modes with n=5 to 8 in the presence of alpha particles. Each toroidal mode is simulated individually .

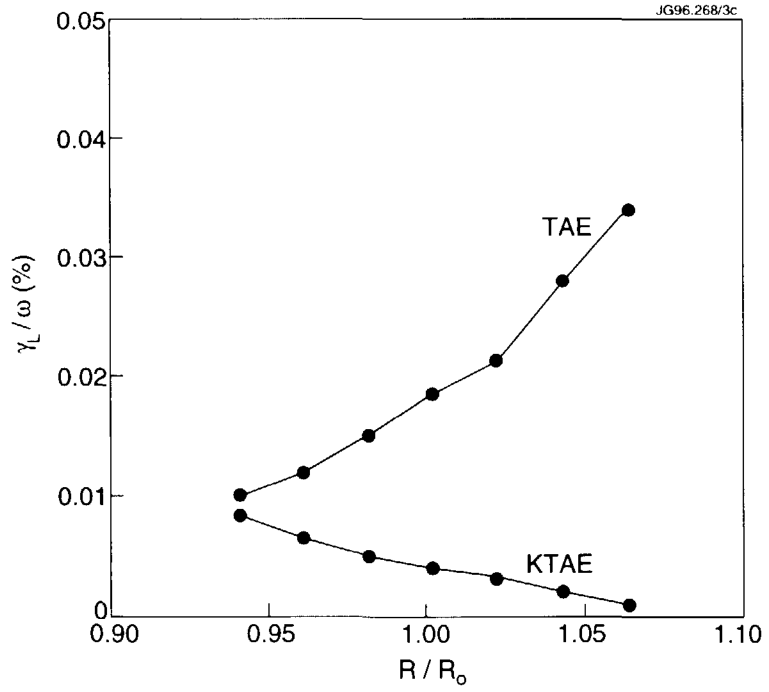

Figure 4 Growth rate of TAE and KTAE modes as a function of the RF resonant layer position in the presence RF generated ions. Optimal excitation is achieved for TAE modes when the resonant layer localized in the low field side of the torus.