Non-Standard Alpha Particle Orbit Effects on the Stability of Alfvén Eigenmodes in JET

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ABSTRACT

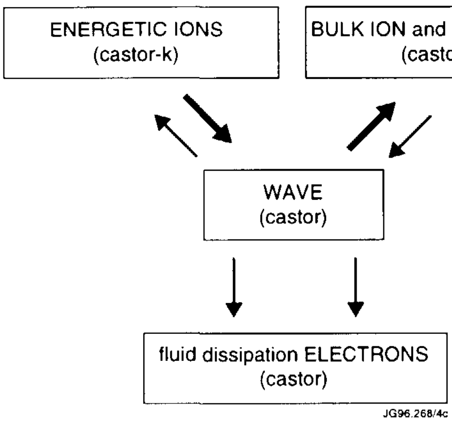
Finite particle orbit width effects on the stability of Global Alfvén eigenmodes are analysed using a hybrid MHD-gyrokinetic model, which includes non-standard orbits. The model is applied to the analysis of the stability of Alfvén eigenmodes in JET plasmas in the presence of alpha particles. It is shown that Kinetic toroidicity induced Alfvén eigenmodes are marginally stable in 50-50% deuterium-tritium equivalent JET discharges.

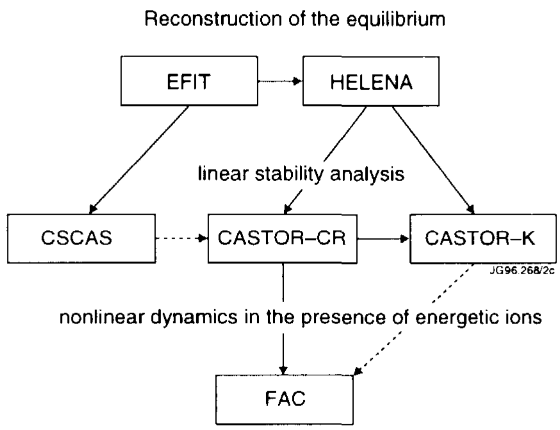
INTRODUCTION

In a tokamak reactor fusion born alpha particles can excite Alfvén waves via particle-wave resonant interaction driven by the free energy available in the radial gradients of the particle distribution. The orbits of alpha particles in present tokamak experiments experience large excursions from the flux surfaces and hence the orbit width is comparable with the width of KTAE and TAE modes even for toroidal mode numbers n=5 to 10. The influence of the finite orbit effects on the stability of Alfvén eigenmodes in JET is studied in the present paper using a Hybrid Gyro-Kinetic-MHD model which includes realistic plasma geometry and Alfvén wave fields including first order ion Larmor radius corrections. The linear stability analysis is performed by the new kinetic extension of the CASTOR code (CASTOR-K), which computes the first order perturbation on the MHD eigenvalue due to energetic ions via a δW_{hot} formulation. This analysis provides stability diagrams for global Alfvén waves in the presence of fusion products or energetic ions generated either by neutral beam injection or by radio frequency heating. The particle orbit effects including non-standard orbits, are particularly important for studying the excitation of core-localized Alfvén eigenmodes, and for the interaction of KTAE and TAE modes with RF generated trapped ions. The trapping of the resonant energetic ions in the potential well created by the unstable wave causes the modes to saturate nonlinearly. The nonlinear interaction of a discrete spectrum of MHD modes with a hot particle source is described by the FAC code [5]. The FAC code is based on an Hamiltonian guiding center scheme for the particle motion in the presence of a field perturbation in conjunction with the self consistent temporal update of the phase and amplitude of the wave. The method allows the determination of the saturation amplitude of the wave and the consequent redistribution or loss of the energetic particles.

MODEL

Using the MHD equilibrium reconstructed by EFIT and HELENA, the linear normal-mode analysis is performed by the spectral codes CSCAS and CASTOR-CR. The linear MHD model includes first order finite ion Larmor radius effects and the perturbed parallel electric field.





The contribution of energetic ions is included perturbativelly. The CASTOR-K code computes the first order perturbation on the MHD eigenvalue due to the resonant interaction between the wave and the energetic particle population using a gyro-kinetic model. The resonant Landau damping from thermal particles is included in the same fashion. The fast particle energy principle including finite orbit widths can be written as follows [2].

$$\delta W_{hot} = -\frac{2\pi^2}{Zem^2}\sum_{\sigma}\int dP_{\phi}dEd\mu \sum_{p=-\infty}^{\infty} \tau_b(\omega - n_0\omega_*)\frac{\partial F}{\partial E}\frac{|Y_p|^2}{\omega + n_0\omega_D + (n_0 q + p)\omega_b},$$

where the bounce and precession frequencies are $\omega_b = \langle\dot{\theta}\rangle$ and $\omega_d = \langle\dot{\phi}\rangle$. The perturbed Lagrangian is bounce averaged over the particle orbits and expanded in Fourier harmonics of the periodic particle motion with the Fourier coefficients defined as

$$Y_p = \oint \frac{d\tau}{\tau_b} L^{(1)} e^{ip\omega_b\tau}, \quad \omega_* = \frac{\dfrac{\partial F}{\partial P_\phi}}{\dfrac{\partial F}{\partial E}}.$$

The term proportional to ω represents the gradients in velocity space, giving origin to the Landau damping, while the term proportional to $n_0\omega_*$ represents the free energy available due to the spatial gradients in the distribution function.

The growth rate of a marginally stable wave is given by,

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

The six dimensional phase-space based on the coordinates $E, P_\phi, \mu, \tau, \alpha$ and ϕ is related to the usual coordinates $(\vec{x}, \vec{v})$ by the Jacobian:

$$d^3x d^3v = \frac{1}{m^2 Ze} dE dP_\phi d\mu d\tau d\alpha d\phi.$$

The phase-space integration is performed using both numerical and analytical procedures. The gyro-averaged description of the motion of the particle's guiding center accounts for one dimension (the gyro angle). Using the periodicity of the unperturbed orbits in the poloidal coordinate, the perturbed Lagrangian is decomposed in Fourier harmonics and the poloidal angle integration is performed using Fourier transforms. Only periodic perturbations in the toroidal direction are considered, thus the integration over the toroidal angle is performed analytically. Since only the resonant part of the integral is required, the energy integration is done analytically over the pole contributions. The remaining two integrations (μ, P_ϕ) are performed numerically using a specific algorithm developed for this problem.

The gyro angle	α	analytical	average procedure
The Poloidal angle	θ	numerical	Fourier transform
The Toroidal angle	ϕ	analytical	Fourier decomposition
The Energy	E	analytical	integration over the poles
The Magnetic moment	μ	numerical	binary search algorithm
The Toroidal momentum	P_ϕ	numerical	binary search algorithm

The accuracy of the CASTOR-K code is assessed by comparison with the analytic theory in the small orbit width limit and a benchmark test with the non-linear FAC code.

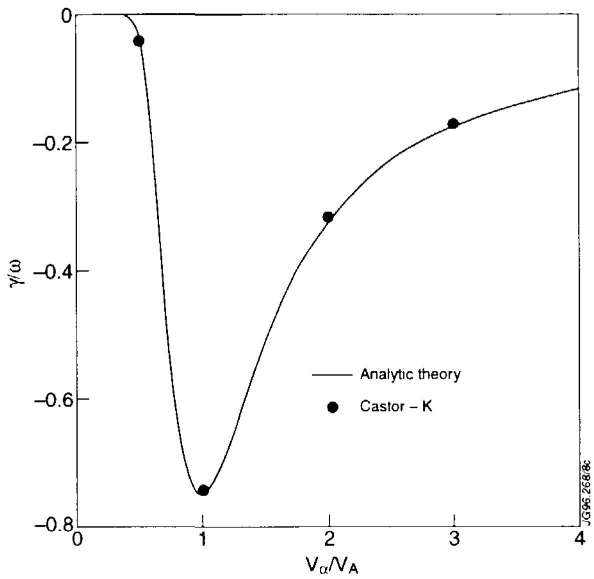


Figure 1: Comparison of the CASTOR-K code with the analytic theory in the small orbit width limit

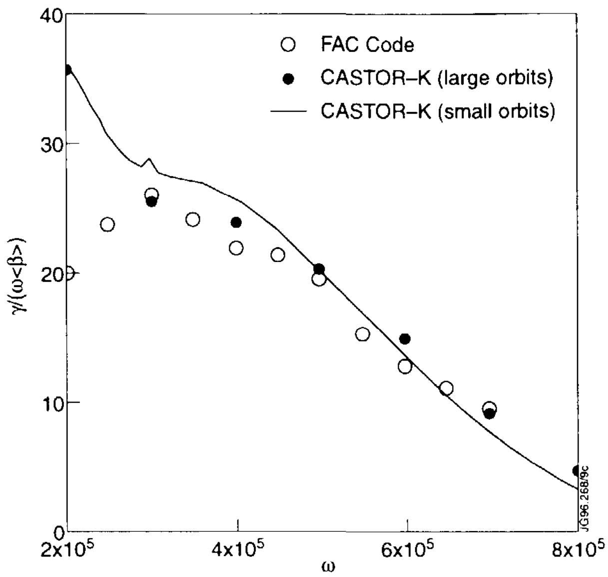
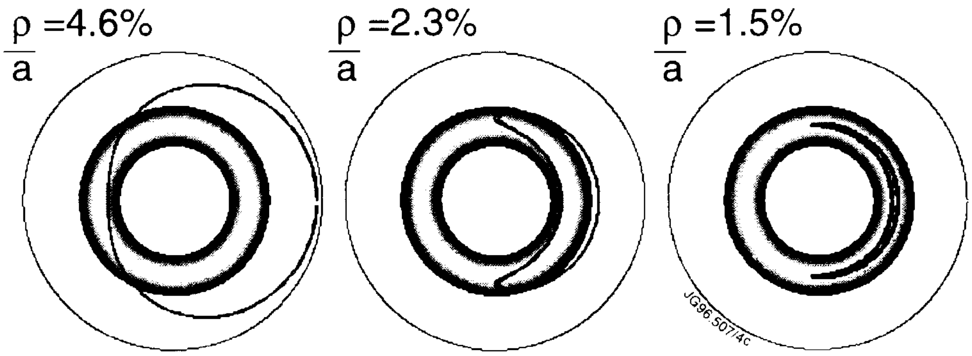


Figure 2: Benchmark of the CASTOR-K code with the nonlinear FAC code

In the large orbit limit the particles drift away from the flux surfaces and the interaction with a localized mode is significantly reduced. In this regime the precession drift frequency is comparable with the transit and bounce frequencies. By increasing the particle Larmor radius the trapped banana orbits become non-standard (potato orbits).



In JET the interaction of energetic ions with KTAE modes with different toroidal mode numbers is analysed using CASTOR-K. Maxwellian distributions are used with different temperatures. The free energy available in the spatial gradients of the distribution function increases with the energy of the particles, but the interaction with KTAE mode is significantly reduced due to orbit effects when the mode widths is comparable with the orbit widths. Taking this two effects into account there is an optimum tail temperature for the KTAE mode excitation.

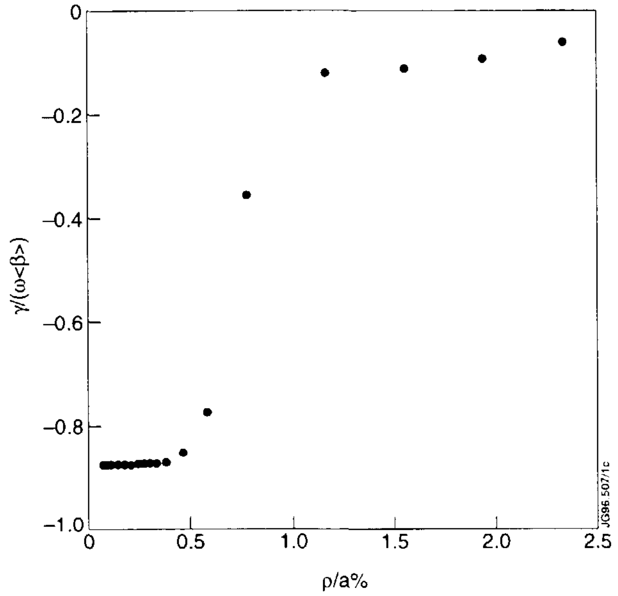


Figure 3: Interaction of an MHD wave n=3 m=4 with particle distributions with different orbit widths represented by ρ/a

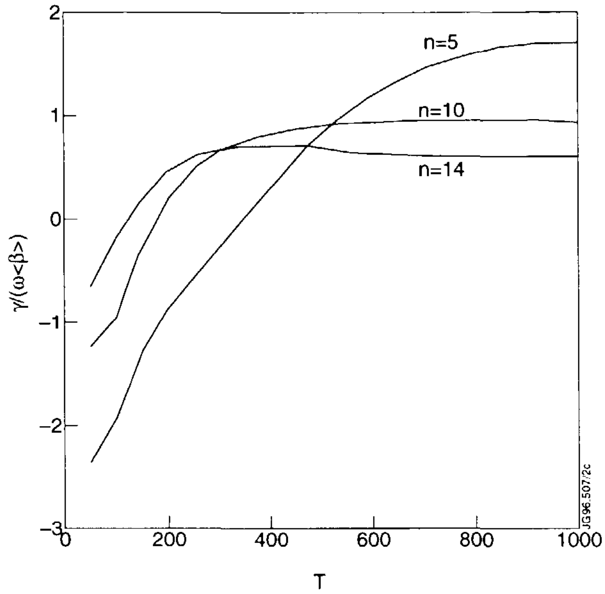


Figure 4: Interaction of n=5,10,14 KTAE modes with Maxwell distributions of alpha particles with different temperatures

The energy exchange between the KTAE modes and the energetic particles also increases with the toroidal mode number n, but the mode width decreases with increasing n, reducing the drive due orbit effects. Considering a JET equilibrium typical for a high performance discharge with $n_e = 5 \times 10^{19}\ m^{-3}$, $B_0 = 3T$, $T_i = 10 \rightarrow 20 KeV$ and $T_e = 10 KeV$ the most unstable modes in the presence of alpha particles are n=5,8 with the drive decreasing rapidilly with n, since the average energy of the alpha particle distribution function is larger than the optimum value.

Toroidal mode number KTAE mode	Threshold Tail Temperature for instability	Optimum Tail Temperature for instability
n=5	340KeV	1200KeV
n=10	170KeV	750KeV
n=14	120KeV	400KeV

ANALYSIS OF ALPHA PARTICLE CONFINEMENT IN JET

Due to a combination of the mode structure and finite orbit effects the most unstable modes in JET in the presence of alpha particles are KTAE modes with intermediate toroidal mode numbers n=5 to 8. The analysis shows that alpha particles have a strong destabilising effect $\frac{\gamma}{\omega} \approx 2\langle\beta_\alpha\rangle$. But due to the alpha particle pressures possible in the JET tritium experiments

$\langle\beta_\alpha\rangle \le 10^{-3}$ and the various damping mechanisms, these modes are expected to be marginally stable. The non-linear simulations performed by the code FAC show that when the KTAEs are 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 typically small $\frac{\delta B}{B} \approx 10^{-5}$ for a single mode.

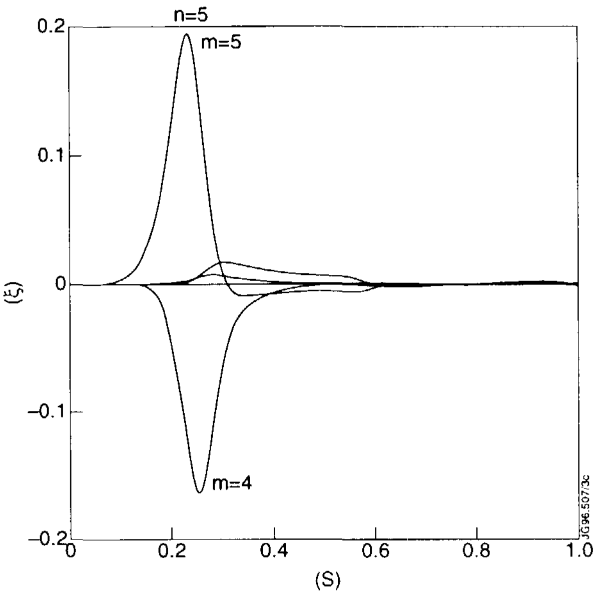


Figure 5: The n=5 core, localized KTAE is computed using CASTOR [3]

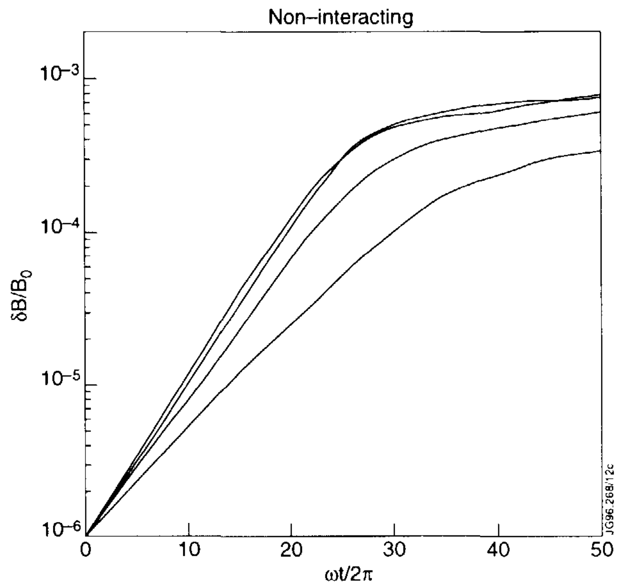


Figure 6: Nonlinear evolution of unstable KTAE modes *with n=5* to n=8 *for β_α=1%.*

CONCLUSIONS

The hybrid Gyro-Kinetic MHD model described in this paper provides a detailed description of the interaction of energetic ions with global plasma waves including realistic geometry, finite orbit widths effects including large non-standard orbits, realistic wave fields with the first order Larmor radius corrections, linear and nonlinear evolution. The accuracy of the CASTOR-K code package is assessed by comparison with analytic results in the small orbit width limit and benchmark test with the FAC code. Applications of the model to JET high performance discharges show that the finite orbit widths effects are important in analysing the contribution of Alpha particles to the stability of TAE and KTAE modes. Alpha particles have a strong destabilising effect on low-n KTAE modes only and for a typical alpha particle pressure and the various sources of damping low-n KTAE modes should be marginally stable in the JET tritium experiments.

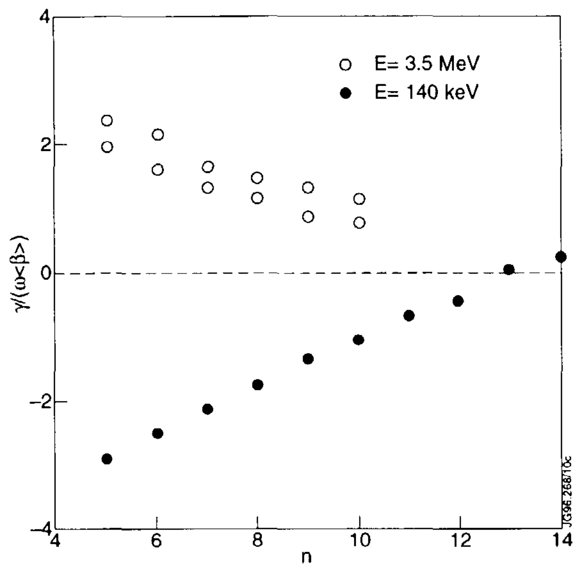


Figure 7: The drive due to a slowing down distribution function of alpha particles (3.5 MeV) and NBI generated ions for KTAE modes as a function of the toroidal mode number.

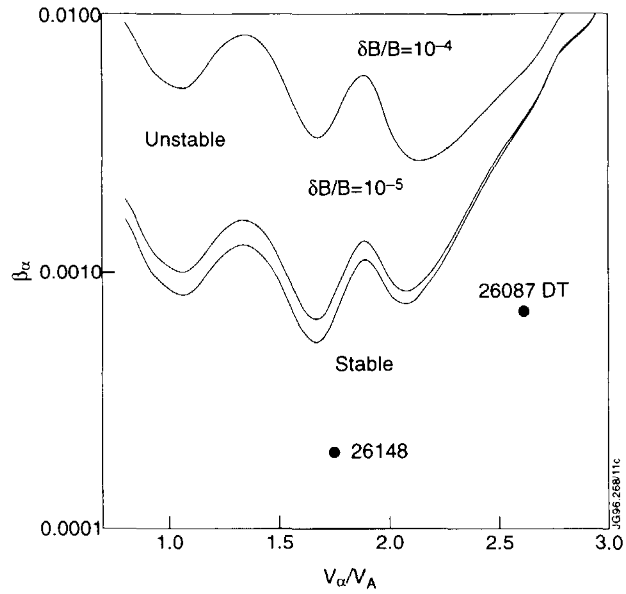


Figure 8: Stability diagram for KTAE modes in JET high performance discharges for 1) the preliminary tritium experiments PTE1 #26148 and 2) a future 50% tritium discharge based on #26087

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