KINETIC TOROIDICITY INDUCED ALFVÉN EIGENMODES IN TOROIDAL SHAPED PLASMAS

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ABSTRACT

The MHD model including first order finite Larmor radius effects of core ions and finite longitudinal electric field is used to compute both the radiative damping and the eigenfrequencies of the Kinetic Toroidicity induced Alfvén Eigenmodes in toroidal plasmas.

INTRODUCTION

The physics of weakly-damped Alfvén modes has been long recognised to be crucial for the confinement of fusion born alpha particles in a tokamak reactor. Within the framework of ideal magnetohydrodynamics (MHD) much attention has been given to the Toroidal Alfvén Eigenmode (TAE), whose eigenfrequency lies in the shear-Alfvén continuum gap. As the TAE eigenfrequency does not satisfy the local Alfvén resonance condition, it is more weakly damped than usual cylindrical shear Alfvén waves, and therefore it can be more easily destabilised by resonant alpha-particles. In hot plasmas, Finite Larmor Radius (FLR) effects[1] convert the TAE mode energy into Kinetic Alfvén waves increasing the outgoing wave energy flux significantly; i.e., the overall damping of the mode via radiative damping. On the other hand for high plasma temperatures, a new branch of Kinetic Toroidal Alfvén Eigenmodes (KTAE) appears and can be driven unstable by energetic particles. Both the radiative damping and the eigenfrequencies of the KTAE spectrum are very sensitive to the plasma parameters. In particular, toroidal and shaping effects in the plasma equilibrium are important.

In this paper the KTAE spectrum is computed for toroidal plasmas with an arbitrary shape including realistic JET scenarios. The FLR kinetic effects and parallel electric field effects are included in the toroidal linear MHD spectral code CASTOR. This model allows one to compute effectively the KTAE spectrum and the radiative damping of TAE and KTAE for arbitrary plasma configurations as a function of the relevant FLR parameter. Included in this spectrum are two types of core localised modes[2], which may be particularly dangerous to plasma confinement as they are peaked near the plasma centre where the drive from fusion alphas or RF ions is strongest. We calculate the radiative damping of the lower frequency mode, and also describe the transition of the upper frequency mode into a KTAE. These results indicate a strategy for a systematic experimental[3] study of the KTAE spectrum.

MHD MODEL INCLUDING FIRST ORDER FINITE LARMOR RADIUS EFECTS

In the outer region away from the resonance surface both KTAE and TAE can be described by the ideal MHD equation, which reduces to a vorticity equation

$$L\phi = b\cdot\nabla\left(\nabla_\perp^2 b\cdot\nabla\right)\phi + \nabla\cdot\left(\frac{\omega^2}{V_A^2}\nabla_\perp\right)\phi = 0 .$$

Here, ω is the eigenfrequency, v_A the Alfvén velocity, b .the equilibrium magnetic field and ϕ is the TAE/KTAE perturbated potential. First order FLR effects of core ions and a finite longitudinal electric field modify the vorticity equation in the boundary layer around the TAE resonance region. These corrections have been calculated in detail by Rosenbluth and Rutherford[4] and lead to the modified current equation:

$$\nabla\cdot j \cong -\frac{3}{4}\frac{i\omega\rho}{B^2}\rho_s^2\nabla_\perp^4\phi - \frac{i}{4\pi\omega}(b\cdot\nabla)\nabla^2 E_{||}, \text{ with } E_{||} \cong -i\rho_s^2(1-i\delta)(b\cdot\nabla)\nabla^2\phi .$$

The vorticity equation equation takes the form:

$$b\cdot\nabla\left(\nabla_\perp^2 b\cdot\nabla\right)\phi + \nabla\cdot\left(\frac{\omega^2}{V_A^2}\nabla_\perp\right)\phi + \frac{1}{4\pi\omega}\rho_s^2(1-i\delta)(b\cdot\nabla)\nabla_\perp^2(b\cdot\nabla)\nabla^2\phi + \frac{3}{4}\frac{\omega^2}{V_A^2}\rho_i^2\nabla_\perp^4\phi = 0 .$$

The structure of this equation is analogous to the structure of the resistive MHD equations with a general complex parameter η defined by: $\eta = 4\pi\omega\rho_s^2\delta\left(\upsilon_e\right) + i4\pi\omega\left(\frac{3}{4}+\frac{T_e}{T_i}\right)\rho_s^2$

For typical of JET parameters, e.g. $\mathrm{Im}[\eta] = 4.4\ 10^{-2}\ T_i[Kev]\ n_e^{-0.5}[cm^{-3}]\ B_T^{-1}[T]$, it is convenient to express η in normalized units $\mathrm{Im}[\tilde{\eta}] = \frac{\mathrm{Im}[\eta]}{\mu_0 R_m V_A} \approx 5.3\ 10^{-10}\frac{T_i[eV]}{B^2[T]}$,which gives $\mathrm{Im}[\tilde{\eta}] \approx 10^{-6}$ in JET auxiliary heated discharges.

KTAE SPECTRUM IN TOROIDAL GEOMETRY USING THE CASTOR CODE

The CASTOR code computes dissipative MHD spectra for arbitrary 2D axisymmetric equilibria. Kinetic modifications to MHD can be modelled by CASTOR within reasonable accuracy by introducing the complex parameter η in the induction equation. In this fashion, a correct result is obtained for normal modes localised in the gap region. Furthermore the coupling between the TAE modes and kinetic Alfvén waves yields the conversion of TAE energy into Kinetic Alfvén waves inside the gap region. Although the propagation of kinetic Alfvén waves across the entire plasma cross-section is not accurately described, the energy transfer from the TAE mode to the KAW is reasonably accurate in this model and since these kinetic waves are strongly damped the radiative damping is well described within this approximation. Applying the Castor code to a reconstructed JET equilibrium, the KTAE spectrum was computed for the shot #34188. In this pulse #34188 several modes were observed during RF heating by the Active Alfvén diagnostic in the passive mode. The modelling shows the existence of two sets of KTAE's with toroidal wave number n=3, one set localized in the central gap and the second set at a minor radius of r=0.5. The central set consists of n=3 KTAEs which are particularly undamped and localized where the RF ion drive is strongest. The frequency of the modes is within 10% of the experimental values and their spacing also agrees with the experimental results using $\mathrm{Im}[\tilde{\eta}] \approx 10^{-6}$ in the modelling. Both branches exhibit equally spaced modes and the damping increases linearly with radial wave number p, for the first branch. For the second branch the damping depends strongly on the mode parity.

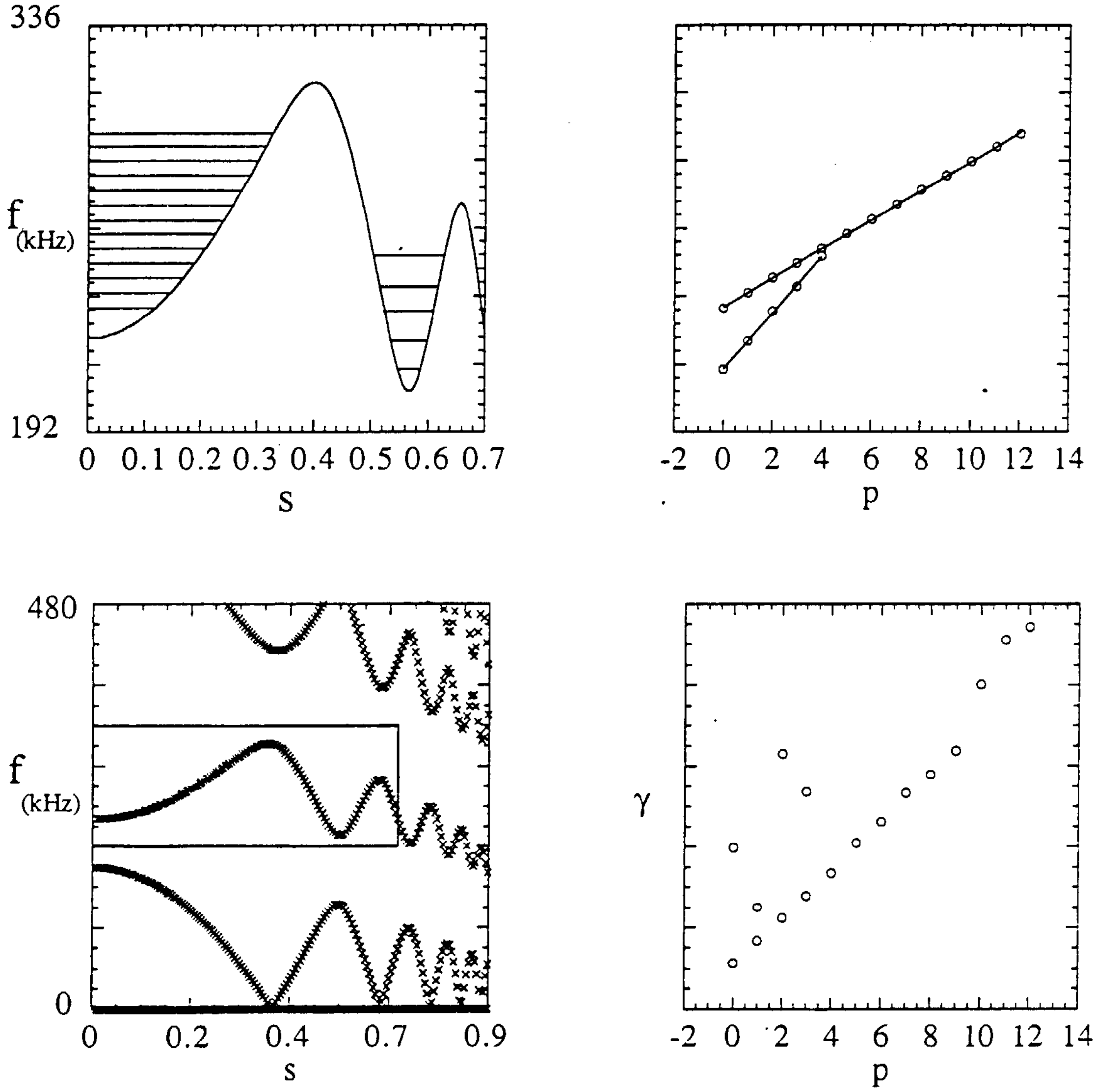

Figure 1 a) KTAE spectrum for the shot #34188 b) frequency of the KTAE modes as function of radial mode number c) continuous spectrum for the shot #34188 d) radiative damping of the KTAE modes as function of radial mode number.

CORE LOCALIZED MODES

Both in TFTR and JET equilibria there exist core localized modes in the low shear and large aspect ratio region. These types of modes can be dangerous to plasma confinement as they are peaked near the plasma center where the drive from alpha particles or radio frequency heated ions is strongest. The FLR effects on the core localized modes can be studied using CASTOR. For this purpose a low shear, large aspect ratio circular equilibrium with a linear q profile varying from q=1 to q=1.25 is introduced, which contains a single gap for n=3 modes. The upper mode does not have significant radiative damping with increasing Larmor radius, in contrast with the lower mode. The KTAE spectrum appears in the hot plasma configuration.

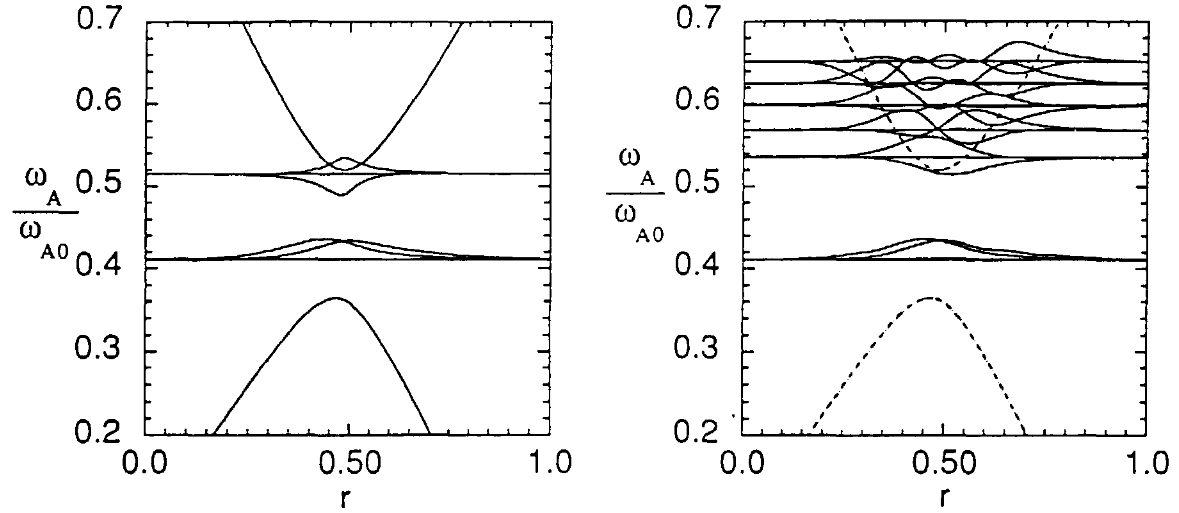

Figure 2 Two n=3 core localized modes that exist in a COLD plasma, In addition the continuous spectrum is displayed, b) the n=3 spectrum for an equivalent HOT plasma, the continuum spectrum (dotted line) is replaced by a discrete KTAE spectrum. The eigenmode.structure is also displayed

CONCLUSIONS

The KTAE spectrum has been computed in toroidal geometry using a reconstruction of JET equilibria. In a cold plasma one or possibly two core localized TAE modes exist, while in a hot plasma the TAE mode has increased radiative damping $|\gamma_{TAE}| > 10\ |\gamma_{KTAE}|$, and a set of undamped KTAE modes appear just above the TAE gap. In a JET hot plasma the model predicts the existence of a set of low n KTAE modes with equally spaced frequencies increasing linearly with radial mode number p and with linearly increasing radiative damping

REFERENCES

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