Global Alfvén Eigenmodes Stability in Thermonuclear Tokamak Plasmas

A.JAUN[1], A.FASOLI[2,3], J.VACLAVIK[4], L.VILLARD[4]

[1] Alfvén Laboratory, EURATOM-NFR Association, KTH, Stockholm, Sweden
[2] Plasma Science and Fusion Center, MIT, Cambridge MA, USA
[3] JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, United Kingdom
[4] CRPP, Association EURATOM-Confédération Suisse, EPFL, Switzerland

Relying on the good agreement observed between the gyrokinetic PENN model and the low n damping measurements from JET, the stability of Alfvén eigenmodes (AE) is here predicted for reactor relevant conditions. Full non-local wave-particle power transfers are computed for the $\alpha-$particles in an ITER reference equilibrium, showing that low $n \simeq 2$ modes are strongly damped and intermediate $n \simeq 12$ with a global radial extension are stable with a damping rate $\gamma/\omega \simeq 0.02$. Even though an excitation of $\alpha-$particle driven instabilities remains in principle possible, this study suggests that realistic operation scenarii exist where all the AEs of global character are stable.

1 Introduction

A critical issue for tokamak reactors is whether Alfvén Eigenmodes (AE) will become unstable and affect the $\alpha-$particle confinement. To be able to predict the pressure $< \beta_{\alpha,crit} >$ above which the resonant $\alpha-$particle drive exceeds the Landau damping from all the species, global fluid and gyrokinetic calculations have been compared with AE damping measurements from JET, **identifying the strong edge magnetic shear (X-point) and the weak central shear as important control parameters to avoid the instabilities** [1]. Low toroidal mode number n damping predictions from models that ignore finite Larmor radius effects are often an order of magnitude smaller than measured in the experiments, while the gyrokinetic Landau damping through mode conversion is generally in agreement within 30%. In this paper, we propose a better model for the wave-particle power transfers to the species $P = P_e + P_{ions} + P_\alpha$ and retain the large orbit width and the Larmor radius of the $\alpha-$particles to all orders. This extends the work carried out in Ref.[2] for the shear-Alfvén wave alone to global gyrokinetic calculations taking into account the mode conversion to the kinetic-Alfvén wave; using the new diagnostic, stability predictions are now made possible also for AEs with intermediate values of $n \simeq 12$ and relatively short wavelengths.

2 Full non-local Power Transfers

When the particle finite orbit width (FOW) depending on the poloidal field B_p and the finite Larmor radius (FLR) depending on the total magnetic fields $B = \sqrt{B_t^2 + B_p^2}$ become large in comparison with the characteristic length of the global wavefield $2\pi k_\perp^{-1}$, the non-local character of the wave-particle interaction must be considered to all orders in the parameter $k_\perp \rho$. Using a gyrokinetic ordering for linear low frequency waves to first order in the inverse aspect ratio a/R, the electromagnetic power resonantly transferred to an ion species can be calculated perturbatively from the Alfvén eigenmode wavefield using

$$P = \frac{1}{2}\Re e \int dV \, \vec{j_{nl}} \cdot \vec{E}^* \ . \tag{1}$$

A non-local expression for the perturbed current density $\vec{j_{nl}}$ is then conveniently written in a straight field line Fourier representation of the electromagnetic potentials $(\vec{A}, \phi) \sim \exp i(k_\rho \rho + m\chi + n\varphi - \omega t)$:

$$\begin{aligned}\vec{j_{nl}} = &2\pi^2 (Ze)^2 qR \int_0^\infty v_\perp dv_\perp \sum_{k_\rho, m, n, l} \exp i \left[k_\rho \rho + m\chi + n\varphi + l(\chi + \chi_k) - \xi_d \sin(\chi + \chi_k) \right] \\ &\frac{J_l(\xi_d)}{nq + m + l} (\omega - \omega_*^T) \frac{F_M}{T} \left(v_\parallel J_0(\xi) \, \vec{e_\parallel} + \frac{i v_\perp}{k_\perp} \, \vec{e_\parallel} \times \vec{k_\perp} \, J_1(\xi) \right) \\ &\left[(\frac{v_\parallel}{c} A_\parallel - \phi) J_0(\xi) + \frac{i v_\perp}{c k_\perp} J_1(\xi) \, \vec{k_\perp} \times \vec{e_\parallel} \cdot \vec{A_\perp} \right]\end{aligned}$$

where

$$\omega_*^T = \omega_* \left\{ 1 + \eta \left[\frac{M}{2T}(v_\perp^2 + v_\parallel^2) - \frac{3}{2} \right] \right\}, \qquad \omega_* = \frac{m}{\rho} \frac{T}{M\Omega} \frac{\partial \ln N}{\partial \rho}, \qquad \eta = \frac{\partial \ln T}{\partial \ln N},$$

$$\xi_d = \frac{qRv_d k_\perp}{v_\parallel}, \qquad \xi = \frac{k_\perp v_\perp}{\Omega}, \qquad k_\perp^2 = k_\rho^2 + \left(\frac{m}{\rho}\right)^2, \qquad k_\rho = \frac{2\pi p}{a},$$

$$v_d = \frac{1}{R\Omega}\left(\frac{v_\perp^2}{2} + v_\parallel^2\right), \qquad v_\parallel = \frac{\omega q R}{nq + m + l}, \qquad \tan \chi_k = \frac{k_\rho}{m/\rho}$$

q is the safety factor, p an integer, F_M a Maxwellian distribution F_M of particles with a mass M, charge Ze, density N, temperature T, and substituting without loss of generality the definitions

$$\frac{F_M}{T} \longrightarrow \frac{F}{M}\frac{\partial \ln F}{\partial \varepsilon}, \qquad \omega_* \longrightarrow -\frac{m}{\rho\Omega}\frac{\frac{\partial F}{\partial \rho}}{\frac{\partial F}{\partial \varepsilon}}, \qquad \varepsilon \longrightarrow \frac{1}{2}(v_\perp^2 + v_\parallel^2), \qquad \eta \longrightarrow 0$$

for other types of distributions such as the slowing down $\alpha-$particles.

3 Validations with experimental Measurements [3, 4]

From the 30 JET discharges which have been reconstructed so far with different magnetic field configurations, values and profiles of the plasma current $I_p = 1 - 4$ MA, density $n_e = 1 - 5 \times 10^{19} m^{-3}$, temperatures $T_e = 2 - 10$ keV, $T_i = 2 - 23$ keV, isotopic mass $A_{eff} = 1 - 3$ and low toroidal mode numbers $|n| = 0 - 2$, two damping mechanisms seem to provide for a damping $\gamma/\omega > 1$ % which is large enough to stabilize an $\alpha-$particle drive typically an order of magnitude smaller. First, the radial localization of the global wavefield due to the high magnetic shear in the plasma edge region provides a

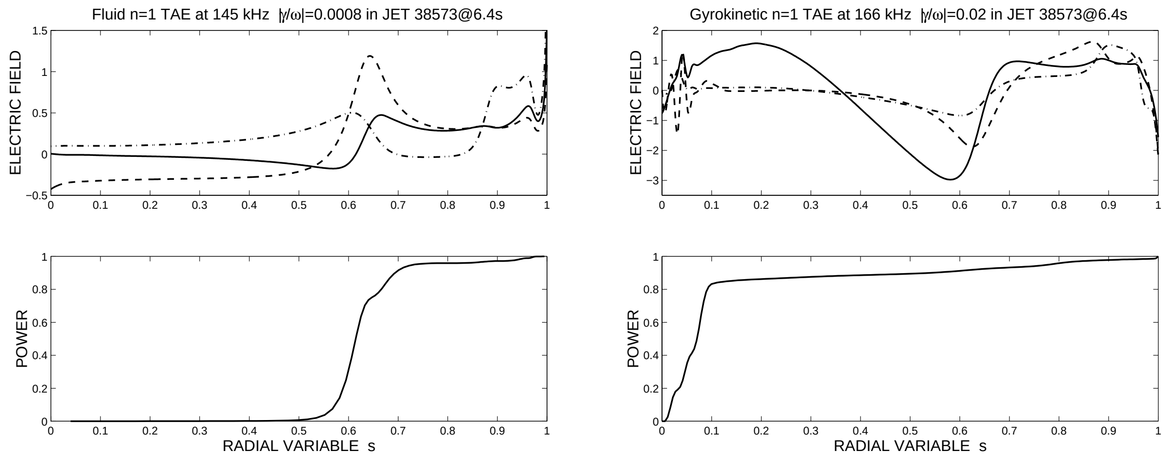

Figure 1: TAE wavefield $\Re e(E_n)$ and total power integrated from the center $\int_0^s ds'P(s')$ using the fluid LION (left) and gyrokinetic PENN codes (right), which predict damping rates $\gamma/\omega = 0.0008$ (fluid) and 0.02 (gyrokinetic) where the experiment measures a TAE at 166 kHz with $\gamma/\omega = 0.02$.

strong electron Landau damping [1] which is thought to be the reason why the saddle-coil antenna has never excited and detected low n modes during the X-point phase with $\gamma/\omega_{exp} < 5-10$ %. The second mechanism acts through the weak magnetic shear in the plasma core and results in the mode conversion into a kinetic Alfvén wave subsequently Landau damped by the electrons. Fig.1 illustrates this with the JET discharge 38573 at 6.4 sec, where the global AE damping rate from the gyrokinetic PENN code [5] $\gamma/\omega_{gk} = 0.02$ is in excellent agreement with the experiment $\gamma/\omega_{exp} = 0.02$, an order of magnitude larger than the prediction from the fluid LION code [6] $\gamma/\omega_{fluid} = 0.0008$ which neglects this mode conversion phenomenon. In general, the damping rates from the gyrokinetic PENN model agree within 30% with the measurements from JET; precise validations of the fast particle power transfer model developed in sect.2 are more difficult because of the lack of precise measurements of the $\alpha-$particle or neutral beam drive. Using the 75 keV beam driven limiter discharge DIII-D 71524 at 1.875 sec and comparing with the stability analysis carried out previously within the drift-kinetic approximation [7], the precision achieved for the fast particle drive can however be estimated better than a factor 2.

4 Global AE Predicted to be Stable in ITER

The stability of toroidal Alfvén eigenmodes with low to intermediate toroidal mode numbers $n = 1-12$ has been examined in a 21 MA, $\beta = 3\%$ reference equilibrium. The fluid LION code generally predicts instability thresholds $< \beta_{\alpha,crit} >= 0.1 - 0.5\%$, while the gyrokinetic PENN code calculations show that Alfvén eigenmodes are stable for all burn conditions envisaged in this scenario. Figure 2 illustrates this with two examples where the non-local power transfers can be compared with the drift-kinetic approximation previously used in Ref.[8]. Because the $n = -2$ TAE wavelength at the $m = 2$ resonance meets the characteristic scale of the kinetic Alfvén wave around $s = 0.2$ (fig.2,left), mode conversion takes place and gives rise to Landau interactions with all three species. Even if the local power transfer $P_\alpha(s)$ oscillates radially in the neighborhood of the resonance, the total $\alpha-$power integrated over the plasma volume remains positive $\int_0^1 dsP_\alpha(s) > 0$, showing that the $n = -2$ kinetic AE (KAE) remains globally stable (in fact strongly damped) for all values of $< \beta_\alpha >$. Non-local wave-particle interactions become important for AE with intermediate mode numbers $n \simeq -12$ (fig.2,right) and contribute to the power transfers $P_\alpha(s)$ with higher order resonances $|l| = 0, 1, 2$. The ratio between the total dissipated

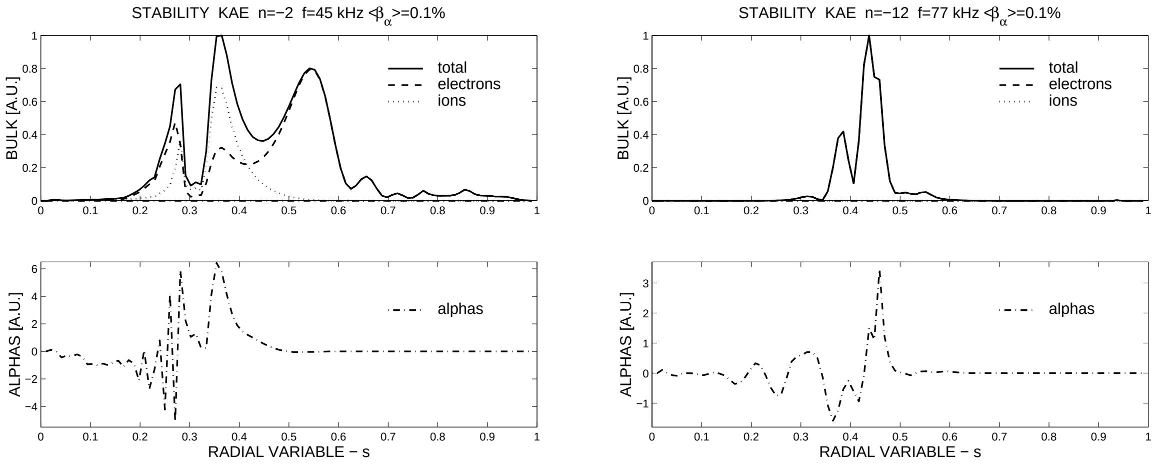

Figure 2: Resonant wave-particle power transfer from the gyrokinetic PENN wavefield to the bulk species $P_e + P_{ions}$ (top) and the $\alpha-$particles P_α (bottom) in the case of a global $n = -2$ TAE at 45 kHz (left) and a radially coupled $m = 11, 12, 13$, $n = -12$ TAE at 77 kHz (right).

and stored power $P/(\omega W) = \gamma/\omega = 0.02$ shows that intermediate $n = -12$ are less damped, but that they remain nevertheless stable for all values of $< \beta_\alpha >$.

To conclude this analysis, one can say that global low to intermediate $|n| = 1 - 12$ AE above 20 kHz should be stable in a relatively large variety of burning ITER-like plasmas.

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References

[1] A. Jaun, A. Fasoli, W. W. Heidbrink, Phys. Plasmas **5** (1998) 2952

[2] N. N. Gorelenkov, C. Z. Cheng, G. Y. Fu, in *Alpha Particles in Fusion Research*, (proc. 5th IAEA Technical Committee Meeting, JET, Abingdon, September 8-11, 1997), edited by J. Jacquinot, B. E. Keen and G. Sadler, JET Report (1997) 153

[3] A. Fasoli *et al.*, Phys. Rev. Lett. **75** (1995) 645, Plasma Phys. Contr. Fusion **39** (1997) B287

[4] W. W. Heidbrink *et al.*, *Phys.Rev.Lett.* **71** (1993) 885

[5] A. Jaun *et al.*, Comput. Phys. Commun. **92** (1995) 153

[6] L. Villard *et al.*, Comput. Phys. Reports **4** (1986) 95,

[7] A. Jaun, J. Vaclavik, L. Villard, Phys. Plasmas **4** (1997) 1110

[8] A. Jaun, J. Vaclavik, L. Villard, in Ref.[2], O.Mo.02