Mode Conversion and Models for the Stability of Alfvén eigenmodes

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ABSTRACT. Different models for global Alfvén eigenmodes are compared from a theoretical point of view to show that a toroidal gyrokinetic calculation is required to correctly take into account the mode conversion and predict the stability of tokamaks in the presence of fast particles.

1 INTRODUCTION

There has recently been a number of controversies [1, 2] over which model to trust when predicting the stability of fusion plasmas, where the inhomogeneity of super-Alfvénic (NBI, ICRF, α) particles drive Alfvén eigenmodes (AEs) that could in turn trigger unacceptable losses of confinement.

Theoretical models are clearly required to extrapolate into thermonuclear conditions that are not accessible today from experimental scalings; meaningful comparisons with measurements are nevertheless possible using the tokamaks that are now in operation to test the ingredients and the parametric dependencies of the underlying physics. Increasingly sophisticated models have been implemented in global wave codes and are categorized as shear-Alfvén wave models (LION [3], NOVA-K [4], CASTOR-K [5], the Frascati code [6], KIN-2DEM [9]), a two-fluid model (TASK-WM [7]) and a gyrokinetic model for the bulk species (PENN [8]); they treat the fast particles either perturbatively (LION, TASK-WM, PENN, NOVA-K, CASTOR-K) or not (Frascati code, KIN-2DEM).

To understand the orders of magnitude discrepancies between various predictions of growth / damping rates and to resolve the argument in terms of toroidal mode conversion, this paper starts with a number of basic considerations in sect.2. The different models are then described and compared on theoretical ground in sect.3, giving a few references to the tests that have been carried out against experimental measurements. The conclusions in sect.4 highlight the present understanding of the mode conversion and the AE stability in tokamaks.

2 UNDERLYING PHYSICS

2.1 MHD, drift, kinetic-Alfvén and resonant wavefields

High frequency ω magneto-hydrodynamic (MHD) perturbations are susceptible to undergo resonant interactions with fast (f) super-Alfvénic particles $v_f > v_A = B_0/\sqrt{4\pi n_i m_i}$ for frequencies that range roughly from the electron (e) or ion (i) drift to the Alfvén frequency: $\omega^* = (\ln nT)' k_\theta T/(m\Omega) \le \omega \le \omega_A = v_A/R \ll \Omega_i$, where $\Omega_i = q_i B/m_i$ stands for the cyclotron frequency of the ions. From a local dispersion analysis of electromagnetic waves, keeping the pressure gradients and the finite Larmor radius (FLR) of the ions, it is known that the drift-waves, the kinetic-Alfvén wave (KAW) and the global MHD wavefield get coupled and yield a relation of the form

$$\omega^2 - \omega\omega_i^* - v_A^2 k_\|^2 \left\{ 1 + k_\perp^2 \rho_i^2 \left[\frac{3}{4} + \frac{T_e}{T_i} \left(\frac{\omega - \omega_i^*}{\omega - \omega_e^*} \right) \right] \right\} = 0 \tag{1}$$

Taking the homogeneous limit $\{\omega_e^*, \omega_i^*\} \to 0$ to recover the standard kinetic-Alfvén wave [10], one immediately sees with Faraday's law how the electrostatic component of a magnetic perturbation $k_\perp \times B \sim E_\|$ is related to the ion Larmor radius dispersion term $k_\perp^2 \rho_i^2$ and yields resonant Landau interactions with passing electrons that move along the magnetic field lines

$$\frac{\gamma}{\omega} = -\sqrt{\frac{\pi}{4}} v_s \frac{v_A}{\Omega_i} k_\perp^2 \exp\left(-\frac{v_A^2}{v_e^2} \right) \overset{v_i \ll v_A \ll v_e}{\propto} -k_\perp^2 \sqrt{A}. \tag{2}$$

In the regime typical of tokamaks nowadays, the Alfvén velocity lies between the ion v_i and electron thermal velocities v_e, so that for a fixed mode structure $k_\perp$ and similar plasma conditions, the electron Landau damping is proportional to the square root of the isotope mass $\sqrt{A}$; this argument has recently been tested against the experiment [11]. Damping occurs also via the collisions between passing or trapped electrons [12, 13], but this collisional damping is negligible compared with the electron Landau damping for fusion relevant regimes – as will be substantiated below in answer to [1].

If the inhomogeneity drifts become sufficiently large $\omega^* > \omega$, the kinetic energy of the particles may be transferred to the wave and provides a finite drive that may overcome the total damping. This can under circumstance occur for the bulk species, but is most easily achieved by fast (energetic) ions. Substituting $i \to f$ in (eq.1) when the fast particle pressure gradient dominates the ions response $\beta_f' > \beta_i'$, it is clear that the wavefield acquires a resonant or energetic character when the normalized fast particle pressure $\beta_f = 8\pi P_{\text{kin}}/B^2$ is comparable with the bulk β.

2.2 Global effects

If the equilibrium scale length become sizable when measured in terms of the perturbation wavelength, global effects lead to important modifications of the local dispersion properties. Take for example the shear-Alfvén wave ($\{\omega^*, \rho_i\} \to 0$ in eq.1) in a tokamak, use a Fourier decomposition toroidally $\exp(in\varphi)$ and poloidally $\exp(im\theta)$ in order to obtain an algebraic representation of the parallel wave vector $k_{\|} = (n + m/q)/R$. Fig.1 illustrates how different harmonics get coupled and yield so-called BAE, TAE, EAE gaps where the plasma beta, the toroidicity and ellipticity prevent shear-Alfvén waves of any frequency from propagating over large portions of the minor radius. Global (radially extended, $k_\perp \neq 0$) solutions however exist within these gaps, the so-called Alfvén eigenmodes (AEs): they often have a mixed T/EAE character and require a global calculation to determine the mode structure $k_\perp(s, \theta)$ and the corresponding damping / drive.

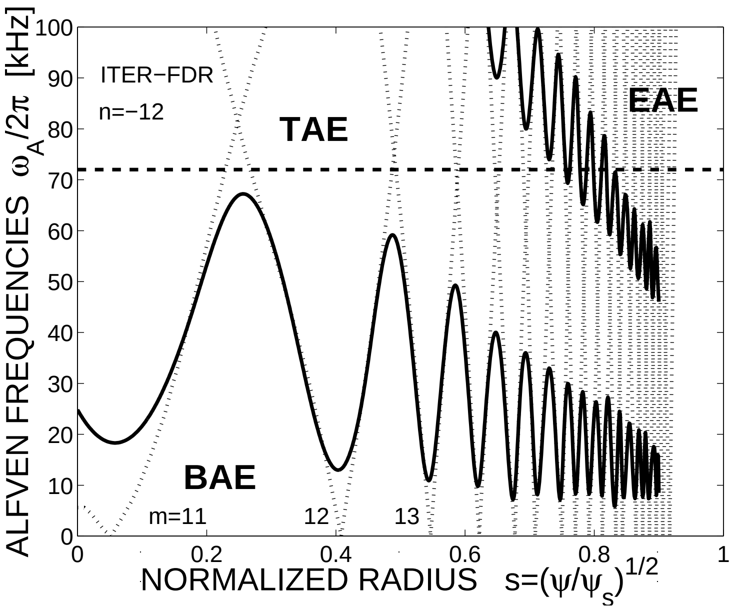

Figure 1: Global effects on the shear-Alfvén wave dispersion.

Global effects modify also the kinetic-Alfvén and the drift waves, which finally get combined with AE wavefields into what we call kinetic AEs (KAEs) [14] and drift-kinetic AEs (DKAEs) [15]. In this sense, Mett & Mahajan's KTAEs [16] are a special type of KAEs that involve only the kinetic-Alfvén wave. Finally, when the energetic particle character dominates the ion response, global solutions exist also for the resonant wavefield and are generally referred to as energetic particle modes (EPMs) [17].

2.3 Mode conversion

Is the fundamental process through which power can be linearly transferred between two waves if their phase velocities somewhere match. First described by Hasegawa & Chen in the presence of an Alfvén resonance, it can be understood locally in Fig.2 in terms of a bi-quadratic dispersion relation of the form $ak_\perp^4 + bk_\perp^2 + c = 0$, where a fast (long fluid scalelength) wave coalesces with a slow (short kinetic scalelength) wave $k^2_{\perp,\mathrm{fast}} \approx k^2_{\perp,\mathrm{slow}}$ in the neighborhood of the resonance. The efficiency of the power transfer depends on the wavefield amplitude and the spatial extension over which the characteristic length and phase of both waves match; a correct evaluation therefore requires solving a 4th order equation, which, for the kinetic-Alfvén wave, amounts to keeping the FLR correction term of $\mathcal{O}(k_\perp^2\rho_i^2)$ in (eq.1).

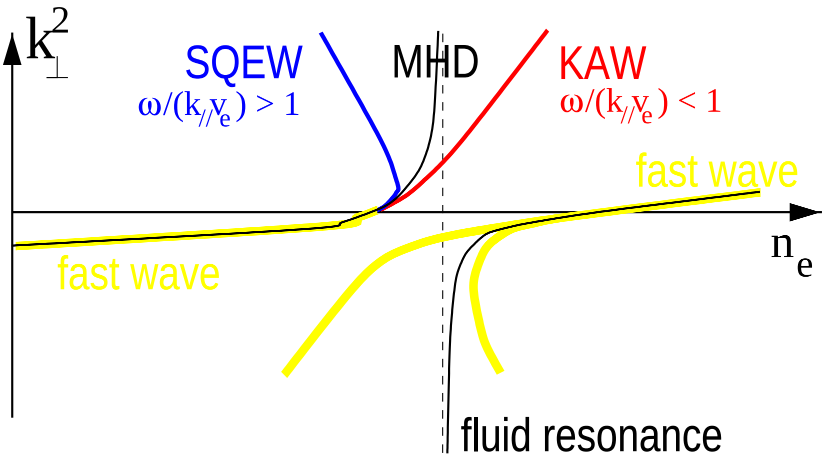

Figure 2: Mode conversion in the neighborhood of an Alfvén resonance.

Several “ad-hoc” models have been proposed to approximate this conversion from the 2nd order (shear Alfvén) fluid MHD equation of the form $ek_\perp^2 + f = 0$, which becomes singular as $e \to 0$ at the resonance. *Continuum damping* [18, 19] calculates the residual absorption of the singularity directly from the MHD model in the limit of an infinitesimal dissipation. The trick describes the correct amount of mode converted power in an unbounded domain [20], but we recently showed in Ref.[21] that it dramatically fails when global effects alter the amplitude and the phase of the fluid wavefield. *Complex resistivity* resolves the singularity of the MHD equations by adding an ad-hoc 4th order term, without consistently keeping the $\mathcal{O}(k_\perp^2\rho_i^2)$ corrections characteristic of the kinetic-Alfvén wave. The mode conversion efficiency calculated in this manner has never been validated even in 1D against a gyrokinetic calculation, but the inconsistent treatment of the dispersion in the neighborhood of fluid resonances is likely to suffer from the same short commings as the continuum damping.

It is finally important to note that mode conversion is not only possible in the neighborhood of fluid resonances and neither does it take place exclusively to the kinetic Alfvén wave: mode conversion can in principle occur anywhere in the plasma where the spatial scale of a fast (fluid, MHD) wave and a slow (drift, surface quasi-electrostatic, kinetic Alfvén, energetic particle) wave match.

2.4 Local and global stability

Following the local analysis from sect.2.1, a harmonic oscillation $\exp(-i\omega t+\gamma t)$ is locally unstable if the drive exceeds the damping

$$\frac{\gamma}{\omega} = \frac{\gamma}{\omega}\bigg|_{\mathrm{drive}} + \frac{\gamma}{\omega}\bigg|_{\mathrm{damp}} > 0. \tag{3}$$

This criterion is extended to global modes by measuring the total power transfer from the particles to the wavefield $P_{tot} = P_f + P_e + P_i$: normalizing with respect to the wave reactive power ωW, a global instability occurs if

$$\frac{\gamma}{\omega} = \frac{P_f + P_e + P_i}{\omega W} > 0 \tag{4}$$

i.e. when a net power flows from the particles to the wavefield and amplifies an initial perturbation. This criterion remains valid in the presence of mode conversion as seen for example with the DKAE instabilities in DIII-D [15], where power flows from the AE wavefield to an electromagnetic drift wave that is Landau damped locally by the electrons, and simultaneously channels from the fast ions driving this drift wave back to the global wavefield to be driven in fact through the conversion layer.

3 GLOBAL MODES & DAMPING MODELS

By analogy with the local analysis (eq.2), the global damping of AEs depends sensitively on the wavefield structure $|\gamma/\omega| \sim k_\perp^2(s,\theta)$ and in particular on the short scale lengths created by mode conversion where $k^2_{\perp,\mathrm{fast}} \approx k^2_{\perp,\mathrm{slow}}$. It is therefore not surprising that the large discrepancies between theoretical stability predictions result more from the modeling of the AE wavefield structure and the mode conversion layers rather than the actual evaluation of the drive or damping.

3.1 Shear-Alfvén wavefield & ad-hoc mode conversion models

Neglecting all possible couplings to kinetic waves, fluid modes such as the G/T/EAE can be described directly with the quadratic (shear-Alfvén) fluid MHD equations; solutions have been obtained numerically using codes such as LION, NOVA-K, CASTOR-K and analytically with a ballooning expansion assuming radially localized modes. The fast particle drive [22], ion Landau [23], electron Landau [24, 3] and collisional dampings [25] calculated for these wavefields are however unrealistically small ($|\gamma/\omega| < 0.001$) compared with the measurements from present day experiments.

3.1.1 Ad-hoc continuum damping

The resonance absorption trick [19] has been used to regularize the MHD singularity when a global wavefield is formed in the presence of Alfvén resonances; the so-called continuum damping of AEs has first been computed numerically [26, 27], implemented in the LION and CASTOR codes and solved analytically [28, 29] for radially localized modes. Using two cold resistive fluids for validation purposes, we repeated such calculations with the PENN code in Ref.[8] by writing the current perturbation along the magnetic field as

$$j_{\|} = -\frac{i\omega}{4\pi}\left\{\frac{\omega_p^2}{\omega(\omega+i\nu_e)}\right\}E_{\|} \quad \rightarrow \quad -\frac{\omega_p^2}{4\pi\nu_e}E_{\| } \tag{5}$$

where the term $\omega(\omega + i\nu_e)$ in the denominator is first replaced by $i\omega\nu_e$ to reduce the 4th order equation in $k_\perp$ down to 2nd order (neglecting the electron inertia in the momentum balance) before taking the collisionless limit $\nu_e \rightarrow 0$. The large continuum damping $|\gamma/\omega| \geq 0.01$ obtained suggested first that only gap modes (having no intersection with the shear-Alfvén continuum) can be observed in actual plasmas. Serious contradictions have been found since both within theory [21] and the experiments [30, 31]; weakly damped modes have been measured with large fields in the neighborhood of Alfvén resonances with continuum damping rates exceeding the damping from mode conversion and the measurements by more than an order of magnitude [30]. Such arguments show that the continuum damping of global AEs is misleading and that shear-Alfvén continuum plots such as Fig.1 are of little value to predict the damping and even the existence of AEs.

3.1.2 Ad-hoc radiative damping

If a TAE mode is strongly localized within a toroidicity gap and the peaking of the wavefield such that mode conversion becomes possible where $k^2_{\perp,\mathrm{TAE}} \approx k^2_{\perp,\mathrm{KAW}}$, the amount of power "radiated away by the kinetic-Alfvén wave" can be calculated perturbatively directly from the shear-Alfvén wavefield [32, 33]. Assuming that all the power is finally absorbed in the vicinity of the conversion region (excluding reflections and fast particle drive on the kinetic Alfvén wave), the so-called radiative damping has been evaluated with the NOVA-K code. Choosing a KAE in JET where the gyrokinetic PENN code a priori predicted that this particular conversion / damping mechanism is dominant (Fig.1 in Ref.[31]), the radiative damping and the electron Landau damping obtained from a self-consistent gyrokinetic description of the global wavefield [34, 31] are found to agree within approximatively 20% [31, 34]. The problem with an ad-hoc evaluation of radiative damping is that it is not a priori possible to know if other conversion mechanism exist and dominate; choosing another KAE where the PENN code predicts that conversion takes place because of weak magnetic shear in the core, order of magnitude discrepancies appear between the damping from the two codes [34, 31]. An ad-hoc radiative damping model is for example unable to reproduce the isotope scaling from Ref.[11], for which good agreement has been achieved between PENN and the measurements from JET.

3.1.3 Ad-hoc complex resistivity

It was apparent in (eq.5) how it is possible to form a 4th order equation with a small change to the resistive MHD by adding an imaginary part to the plasma resistivity [35]:

$$j_{\|} = -\frac{i\omega}{4\pi}\rho_s^2\left(\frac{2\omega}{\omega_A}\right)^2\left[\underbrace{i\delta(\nu_e)}_{\text{resistivity}} - \underbrace{\left(\frac{3}{4}+\frac{T_e}{T_i}\right)}_{\text{KAW mock-up}}\right]E_{\|}. \tag{6}$$

The kinetic-Alfvén wave dispersion and the mode conversion is mocked-up, keeping a tiny collisional dissipation $\sim \nu_e$ to reproduce weakly damped KTAE modes that were predicted analytically by Mett & Mahajan [16]. Implemented in the CASTOR-K code for global wavefields, the results from the complex resistivity model are however often in contradiction with the gyrokinetic calculations from the PENN code. This not surprising, since the dispersion is here not consistent with the FLR correction $\mathcal{O}(k_\perp^2\rho_i^2)$ characteristic of the kinetic-Alfvén wave. The 4th order complex resistivity equation is very different from a consistent gyrokinetic ordering, the amount of power converted where the spatial scales match $k^2_{\perp,\mathrm{TAE}} \approx k^2_{\perp,\mathrm{KAW}}$ is altered and the Landau damping, which should be a selective 2nd order differential operator to reproduce the $|\gamma/\omega| \sim k_\perp^2$ dependence of (eq.2), is entirely absent. This explains the large qualitative differences between the complex resistivity spectrum calculated by the CASTOR-K code and the gyrokinetic spectrum. To our knowledge, it was never possible to show a quantitative agreement between damping rates predicted using the complex resistivity model and the measurements from the JET tokamak.

3.2 Electromagnetic gyrokinetics (GK)

By now, it should be clear that a consistent description of the coupling between a fluid AE and the kinetic-Alfvén wave requires a gyrokinetic description of the passing bulk ions with FLR corrections at least to $\mathcal{O}(k_\perp^2\rho_i^2)$. This has first been derived in Ref.[36] and implemented in the PENN code [8]. The perturbed current contributes mainly along the magnetic field and can be written symbolically using the dispersion function[1]

$$j_{||} = -\frac{i\omega}{4\pi}\left\{\frac{2\omega_{pe}^2}{k_\varphi v_e}\left[1-Z^{\rm Sh}\left(\frac{\omega+i\nu_e}{|k_\varphi|v_e}\right)\right]+\nabla_\perp^\dagger\left[\frac{\omega_{pi}^2}{k_\varphi^2\Omega_i^2}Z^{\rm Sh}\left(\frac{\omega}{|k_\varphi|v_i}\right)\right]\nabla_\perp+\ldots\right\}E_{||}$$
$$+\{\ldots\}E_n+\{\ldots\}E_b+\text{neoclassical}+\text{drifts} \tag{7}$$

The second order term $v_i^2/\Omega_i^{-2}\nabla_\perp^\dagger\nabla_\perp \sim -\rho_i^2k_\perp^2$, reproduces the FLR induced kinetic-Alfvén wave dispersion (eq.1) with the real part of the second dispersion function. In addition, a number of terms are not shown here and contribute in a non-evident manner to account for the proper amount of mode conversion in toroidal geometry. The expression shows explicitly how the resistive damping (collision frequency ν_e in the imaginary part of the first dispersion function) differs from the selective Landau damping (ω in the imaginary part of the second dispersion function). Most important compared with the previous models, is that the Landau damping is here proportional to the electrostatic component $E_{||}$: solving Maxwell's equations for an Alfvénic perturbation $\nabla_\perp\times B=\nabla_\perp\times\nabla\times E\sim E_{||}$ with the spatial scale self-consistently described with FLR effects, this reproduces the selective damping $\sim k_\perp^2$ from (eq.2) that affects mainly the shorter wavelength kinetic-Alfvén wave. To perform analytically the integration over the resonant denominators $(\omega-k_{||}v_{||})^{-1}$ and formulate a differential problem in both the radial and poloidal directions, the wave-particle resonance has been approximated assuming passing particles and using a functional dependence for the parallel wave vector, e.g. $k_{||}\simeq k_\varphi^{\rm TAE}(s,\theta)=1/(2qR)$. This approximation can be tested a posteriori in two manners:

- by monitoring the sensitivity of the global damping on different choices that are plausible $k_\varphi\in\{(2qR)^{-1},(qR)^{-1},n/R\}$,
- comparing the complex eigenvalue calculated directly from the model [36] with the damping evaluated perturbatively from the gyrokinetic wavefields $\gamma/\omega=P_{tot}/(\omega W)$. To give a quantitative answer to the controversy in Ref.[1], the drift-kinetic power for passing electrons P_{DKe} [3] is here extended to account for what turns out to be

[1]Shafranov's definition $Z^{\rm Sh}(\xi)=-\xi Z^{\rm NRL}(\xi)$

a really negligible damping from trapped electrons [38]

$$P_e = (1-\alpha_t)P_{DKe} + \alpha_t P_{col} \quad \text{with} \quad \alpha_t = \sqrt{\frac{B}{B_{max}}} \tag{8}$$

$$P_{col} = -\frac{(q\omega)^2}{2}\int dV\left(\frac{\nu}{\omega^2+\nu^2}\right)\frac{n_e}{T_e}|\Phi|^2 \tag{9}$$

where $\nu = (\nu_{ee}+\nu_{ei})R/\rho$ and Φ is the electrostatic potential calculated here consistently with the gyrokinetic model. The power transfer with passing fast- and bulk ions is evaluated with the non-local expression from Ref.[39] valid to all orders in the Larmor radius $k_\perp\rho_i > 1$.

Except for DKAE modes where the mode conversion takes place to an electromagnetic drift wave [15, 37] and depends rather sensitively on the choice of k_φ, these self-consistency checks largely justify the approximations made. They show that the global damping of AEs depends mainly on the location where the conversion occurs, which determines how much power is converted and finally deposited by the kinetic Alfvén wave. In other words, the global damping of AEs depends only weakly on the local Landau damping that affects only the distance the wave covers before it is ultimately damped.

The strength of our approach is that it does not a priori rely on any particular mode conversion mechanism that has been mocked-up from an informed guess; following the dispersion and damping of both the fast and slow global wavefields, mode conversion spontaneously occurs where $k^2_{\perp,\text{fast}} \approx k^2_{\perp,\text{slow}}$. Five conversion mechanisms have been found so far, of which four occur to the kinetic Alfvén wave and only two had been expected from heuristic arguments. They are illustrated in the sketch of Fig.3:

1. Near the plasma center, where the aspect ratio is large and the shear is sufficiently weak, the kinetic-Alfvén wave expands radially until it matches the global fluid scale [31]. This mechanism reproduces the global AE dampings measured in a set of similar JET discharges, showing with (eq.2) that the gyrokinetic mode structure correctly changes with the isotope mass [11].

2. Within gaps, mode conversion sometimes reduces to radiative damping if the kinetic-Alfvén wave is damped in the vicinity of this gap, so that both models reproduce the global damping measurements from JET to a good degree of accuracy [31, 34]. Global effects within a single gap can however also split a weakly damped AE into KAEs [14, 40], couple adjacent gaps to form high$-n$ global KAE [37] and the fast particles may even drive the kinetic Alfvén wave [37].

3. At Alfvén resonances, mode conversion is generally not as efficient as continuum damping. The wavefield and damping predicted by the PENN and CASTOR-K

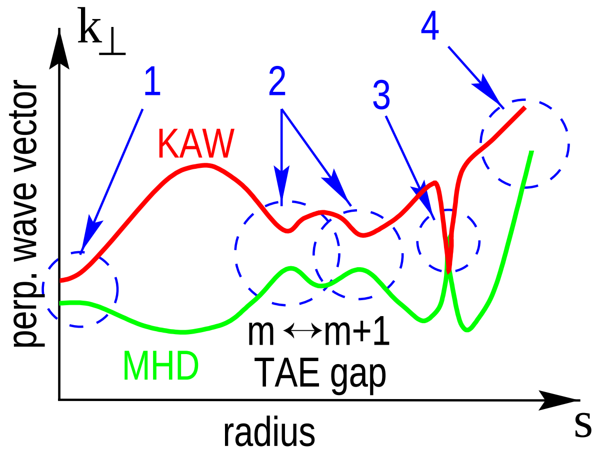

Figure 3: Sketch of four mode conversion mechanisms between the fluid (MHD) and kinetic Alfvén (KAW) wavefields.

codes have been compared with measurements from JET in Ref.[30, 31] showing clear contradictions with continuum damping model.

4. In the plasma edge, the large magnetic shear associated with the plasma shaping (X-point) squeezes the wavefield radially and triggers a mode conversion. The strong global damping rate that results has been tested in the time evolution of Ref.[31].

5. Mode conversion to electromagnetic drift waves becomes possible in the neighborhood of rational surfaces where $k_{||} \simeq 0$ if $\omega_*/\omega_{TAE} \simeq 2nq^2(\rho/a)^2(R\omega_{pi}/c)$ approaches unity, so that drift-kinetic AEs (DKAEs) become unstable. They provide for a plausible mechanism for the instabilities observed in the TAE frequency range of DIII-D [41, 15]; their modeling is however likely to suffer from the approximative treatment of the parallel dynamics with $k_\varphi = 1/(2qR)$.

So far, the gyrokinetic PENN model with approximate parallel dynamics is the only tool that deals properly with the mode conversion of global wavefields in a tokamak; most toroidal predictions remain therefore to be confirmed using other models.

The KIN-2DEM code [9] from PPPL/Princeton does not presently retain the dynamics of passing ions and therefore misses the mode conversion to kinetic-Alfvén wave that is essential for AEs and perhaps also important for kinetic ballooning modes (KBM). A gyrokinetic model including the main ingredients has recently been formulated in Ref.[42] and might be implemented in a future version of the NOVA code. A model for electromagnetic micro-instabilities is currently under development at CRPP/Lausanne for low β plasmas in simple toroidal geometry and includes the parallel dynamics of passing and trapped bulk particles to all orders in $k_\perp\rho_i$ [43]; the model retains the mode conversion both to the kinetic-Alfvén and the drift waves and will soon be used to confirm and extend the present knowledge beyond the FLR approximation. In parallel, a new electromagnetic model for macro-instabilities has been derived for a future version of the PENN code, keeping the complete parallel dynamics of passing bulk- and energetic ions together with large β and arbitrary shape in the limit of small Larmor radii. A complete derivation for the current perturbation along the magnetic field will be given elsewhere, but finally results in an integro-differential expression in configuration space that can be written symbolically as

$$\begin{aligned} j_{\|} = \frac{i\omega}{4\pi}\Bigg\{ -\frac{c(Ze)^3}{m^2T_\perp}\int dv_{\|}F(v_{\|})\int_0^{2\pi}d\theta K(\theta,\theta')JB\left(\left[1-\frac{\omega^*}{\omega}\left(1+\frac{\eta v_{\|}^2}{2T_\perp}\right)\right]\times\right.\\ \left.\times\left[\left(1+\frac{m^2T_\perp}{(ZeB)^2}\Delta_\perp\right)\left(\Phi-\frac{v_{\|}}{c}A_{\|}\right)+\frac{mT_\perp}{ZeB}B_{\|}\right]\right)+\text{drifts}\Bigg\} \end{aligned} \tag{10}$$

The kernel $K(\theta,\theta')$ clearly plays an essential role here, since it contains the wave-particle resonances that are integrated numerically over $dv_{\|}$ and couples different poloidal locations through the integral operator. Finite Larmor radius corrections appear explicitly with the second order operators $\Delta_\perp$ and inhomogeneities with the drift frequency ω^*. Resonant effect from energetic particles are not shown here, but are also kept in the small Larmor radius approximation. The physics we hope to study with this new model ranges down in frequency from the energetic-particle-kinetic AEs, drift-kinetic AEs, beta-induced AEs and finally the non-ideal counterparts of MHD instabilities such as KBMs, internal kink and resistive-wall modes.

4 CONCLUSIONS

Different models currently used to predict the stability of AEs have been compared and discussed from the point of view of mode conversion. Theoretical arguments underline that a global gyrokinetic model is required for a consistent description and show a number of contradictions with ad-hoc models that mock-up this phenomenon. Ultimately, however, the experiment is the only and best referee: the high quality damping measurement from JET [44] are far more delicate to reproduce quantitatively than the qualitative comparison of instability thresholds. These measurements have so far only been reproduced with the variety of mode conversion mechanisms discussed above. This should be enough arguments to resolve most of the controversies and should motivate other groups to develop an independent check of the global gyrokinetic predictions that stem now exclusively from the PENN code.

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References

[1] Y. Kolesnichenko, S. Sharapov, argued that trapped electrons collisional damping dominates over the Landau damping of global kinetic-Alfvén wavefields, questionning calculations shown by A. Jaun *et al.* at the *5th IAEA-TCM on Energetic Particles*, Naka (1999)

[2] A. Jaun *et al.* showed orders of magnitude discrepancies in the predictions from ad-hoc shear-Alfvén wave damping models and the Landau damping from toroidal mode conversion, at the *5th IAEA-TCM on Energetic Particles*, Naka (1999)

[3] L. Villard, S. Brunner, J. Vaclavik, Nucl. Fusion 35 (1995) 1173

[4] C. Z. Cheng, Phys. Reports 211 (1992) 1

[5] W. Kerner *et al.*, J. Comput. Phys. (1998) 271

[6] S. Briguglio *et al.*, Phys. Plasmas 2 (1995) 3711

[7] A. Fukuyama *et al.*, (Proc. 17th Fusion Energy Conf., Yokohama) IAEA-CN-69/THP2 (1998), also in Comput. Phys. Reports 4 (1986) 137

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

[9] H. Qin, W.M. Tang, G. Rewoldt, Phys. Plasmas 6 (1999) 2544

[10] A. Hasegawa, L. Chen, Phys. Rev. Lett. 35 (1975) 370

[11] A. Fasoli, A. Jaun, D. Testa, Phys. Lett. A 265 (2000) 288

[12] M.N. Rosenbluth, D. Ross, N. Kostomarov, Nucl. Fusion 12 (1972) 3

[13] V.S. Belikov *et al.*, Sov. J. Plasma Phys. 3 (1977) 146

[14] A. Jaun *et al.*, Plasma Phys. Control. Fusion 39 (1997) 549

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

[16] R.R. Mett, S.M. Mahajan, Phys.Fluids B 4 (1992) 2885

[17] L. Chen, *Theory of Fusion Plasmas* (Proc. Int. Workshop, Varenna, 1988) Editrice Compositori, Bologna (1988) 327

[18] Seminal work on solving real space singularities can be found in articles from Ginzburg (1960) and the textbook by K. Budden, *Radio Waves in the Ionosphere*, Cambridge University Press (1961)

[19] J.A. Tataronis, J. Plasma Phys. 13 (1975) 87

[20] L. Chen, *Waves and Instabilities in Plasmas*, Lecture Notes in Physics Vol.12, World Scientific, Singapore (1987)

[21] A. Jaun *et al.*, Phys. Plasmas 5 (1998) 3801

[22] G.Y. Fu, J.W. Van Dam, Phys.Fluids B 1 (1989) 1949

[23] R. Betti, J. Friedberg, Phys. Fluids B 4 (1992) 1465

[24] J. Candy, M.N. Rosenbluth, Nucl. Fusion 35 (1995) 1069

[25] N.N. Gorelenkov, S.E. Sharapov, Phys. Scripta 45 (1992) 163

[26] K. Appert *et al.*, Nucl. Fusion 22 (1982) 903

[27] L. Villard, G.Y. Fu, Nucl. Fusion 32 (1992) 1695

[28] F. Zonca, L. Chen, Phys. Rev. Lett. 68 (1992) 592

[29] M.N. Rosenbluth *et al.*, Phys. Rev. Lett. 68, 596 (1992)

[30] W.W. Heidbrink *et al.*, Phys. Plasmas 4 (1997) 3663

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

[32] H.L. Berk, R.R. Mett, D.M. Lindberg, Phys. Fluids B 5 (1993) 3969

[33] R.R. Mett, E.J. Strait, S.M. Mahajan, Phys. Plasmas 1 (1994) 3277

[34] G.Y. Fu, A. Jaun, *6th Easter Plasma Meeting*, Turin (2000)

[35] J.W. Connor *et al.*, (Proc. 21st EPS Conf., Montpellier), European Physical Society, vol.18B, part II (1994) 616

[36] S. Brunner, J. Vaclavik, Phys. Fluids B 5 (1993) 1695

[37] A. Jaun, A. Fasoli, J. Vaclavik, L. Villard, Nucl. Fusion 40 (2000) 1343

[38] A. Jaun *et al.*, (Proc. 18th Fusion Energy Conf., Sorrento) IAEA-CN-77/THP2-19 (2000),

[39] A. Jaun *et al.*, (Proc. 17th Fusion Energy Conf., Yokohama) IAEA-CN-69/THP2-23 (1998), Nucl. Fusion 39 Vol. 11Y (1999) 2095

[40] A. Fasoli *et al.*, Phys. Rev. Lett. 76 (1996) 1067

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

[42] C.Z. Cheng, J.R. Johnson, J. Geophys. Res. 104 (1999) 413

[43] G.L. Falchetto, J. Vaclavik, *Theory of Fusion Plasmas* (Proc. Int. Workshop, Varenna, 2000) Editrice Compositori, Bologna (2000) in these proceedings

[44] A. Fasoli *et al.*, Phys. Rev. Lett. 75 (1995) 645

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