Drift- / Kinetic Alfvén Eigenmodes in High Performance Tokamak Plasmas

A. Jaun[1], A. Fasoli[2], D. Testa[2], J. Vaclavik[3], L. Villard[3]

1) Alfvén Laboratory, Euratom-NFR Association, KTH, 100 44 Stockholm, Sweden
2) Plasma Science Fusion Centre, MIT, Cambridge MA 02139, USA
3) CRPP-EPFL, 1015 Lausanne, Switzerland

E-mail: jaun@fusion.kth.se

Abstract. The stability of fast-particle driven Alfvén eigenmodes is modeled in high performance tokamaks, successively with a conventional shear, an optimized shear and a tight aspect ratio plasma. A large bulk pressure yields global kinetic Alfvén eigenmodes that are stabilized by mode conversion in the presence of a divertor. This suggests how conventional reactor scenarii could withstand significant pressure gradients from the fusion products. A large safety factor in the core $q_0 > 2.5$ in deeply shear reversed configurations and a relatively large bulk ion Larmor radius in a low magnetic field can trigger global drift-kinetic Alfvén eigenmodes that are unstable in high performance JET, NSTX and ITER plasmas.

1. Introduction

Because of the large birth velocity of the fusion produced $\alpha-$particles exceeding the Alfvén speed, Alfvén eigenmodes (AEs) can potentially be driven unstable by the pressure gradient and affect the global confinement in a reactor. The regimes where this may occur can not be explored with dimensionless experimental scalings using the tokamaks currently in operation; numerical models are therefore needed to make stability predictions. To be credible, these models have to be validated against existing experimental measurements [1, 2, 3].

The global nature and the frequency of AEs can be understood from fluid MHD models describing shear-Alfvén wavefields "trapped in a toroidal resonator"; global modes result because of the interplay between the plasma current, the plasma shape and the pressure. To determine the stability of AEs, it is necessary to account for the coupling to the kinetic Alfvén wave. This stimulated the development of models such as *continuum damping*, *complex resistivity* and *radiative damping* where this coupling is calculated in an ad-hoc manner directly from fluid MHD modes. The difficulties in finding agreement between the models, more theoretical arguments [4] and the comparisons with experimental measurements [5, 6] motivate the use of a self-consistent gyro-kinetic description for the bulk plasma. Such a model is required to calculate the power transfer between global fluid and kinetic wavefields [7] and correctly predict global damping rates. Consequently, the stability of AEs depends on a variety of *mode conversion* mechanisms that appear where the phase velocities of the shear- and the kinetic-Alfvén wave coincide.

From the ratio between the ions drift- and the TAE frequency $\omega_*/\omega_{TAE} \simeq 2nq^2(\rho/a)^2(R\omega_{pi}/c)$ it appears clearly that a large safety factor $q > 2.5$, a low magnetic field and large normalized Larmor radius ρ/a characteristic of high performance regimes, significantly complicate the stability calculations by introducing new mechanisms for mode conversion to the electro-magnetic drift waves. Global drift-kinetic AEs (DKAEs) [8] are formed that provide plausible explanations for the large fast particle losses observed in low magnetic field DIII-D plasmas [2, 9] and will here be further examined with the PENN code using an approximative $k_\parallel = 1/(2qR)$ to model the resonant wave-particle interaction.

2. Comparisons with measurements from JET

Having tested how the damping of low toroidal mode number $n = 1$ AEs rises with the edge magnetic shear ($|\gamma/\omega| \simeq 0.02 - 0.08$) [5] and decreases with the isotope mass ($|\gamma/\omega| \simeq 0.02 - 0.01$) [6], it became clear the understanding of the mode-conversion in JET made it possible to identify conventional plasma configurations where all the low and high n fast particle driven AEs of global nature are stable.
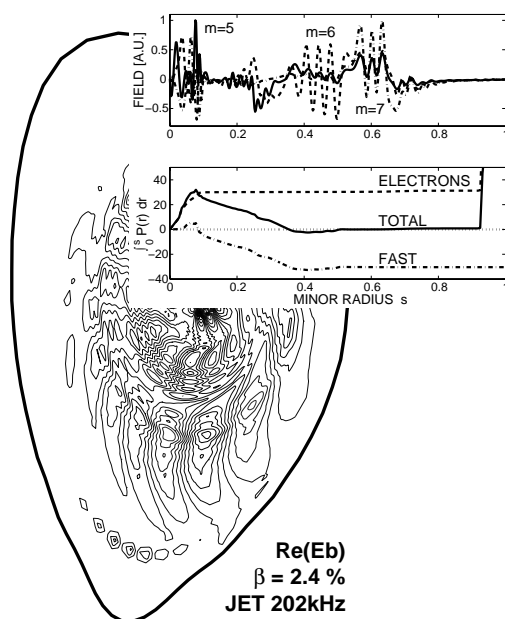

Figure. 1: A global n=6 KAE is stabilized by mode conversion near the X-point for a bulk $\beta > 2.5\%$ in the JET shot 40308.

Recent studies involving ICRH-driven instabilities with intermediate mode numbers (n=5-12), show that also radially localized modes become kinetic and global when the bulk plasma β rises, and, in a manner similar to low n modes, are stabilized by the strong shear in the divertor region and the weak shear in the plasma core [11]. Figure 1 illustrates this mechanism with a hot-ion H-mode discharge where an n=6 kinetic AE (KAE) instability in the plasma core ($s \simeq$ 0.2-0.4) extends radially as the bulk pressure rises above $\beta \simeq 1\%$ and mode-conversion is induced in a succession of toroidicity gaps (n_{e0}=3.5×10^{19} m^{-3}, T_{e0}=11.3 keV, T_{D0}=24.9 keV, q_0=0.84, q_{95}=3.5, l_i=0.94, β=2.4%, β_p=0.78, P_{NBI}(140 keV)=10 MW, P_{NBI}(80 keV)=8 MW, P_{ICRH}=4.5 MW). The mode is stabilized when the global wavefield reaches the divertor region and the kinetic Alfvén wave (visible at the bottom of Fig.1) gets heavily Landau damped by the electrons, in good agreement with the stability threshold observed experimentally.

A new class of instabilities is observed in optimized shear discharges, where a non-monotonic safety factor profile $q(s)$ is created by applying lower hybrid power in the pre-heating phase. This results in two internal transport barriers that sustain relatively large pressure gradients: the outer barrier is located in the neighborhood of the q=2 surface and the inner one is associated with a negative magnetic shear [10]. A typical example is given in Fig.2 for the JET discharge 51594, where MSE measurements show that a shear reversal is achieved at the beginning of the main heating phase (t=44.25s, q_0=3.1, q_{min}=2.1 at s=0.4 and q_{95}=5.7) and then slowly evolves due to the current diffusion (t=47.16s, q_0=2, q_{min}=1.5 at s=0.25 and q_{95}=5.4). The inner barrier is produced at t=45.2s around s=0.2 and the outer at t=45.9s around s=0.6. The spectrum of the magnetic fluctuations in Fig.2 shows that global instabilities with low to intermediate n=1-7 appear in the frequency range 70-170kHz. These modes are excited at relatively low ICRF power ($P_{ICRF} > 1$MW) and satisfy the local scaling $0.01 < \omega_{*D}/(n\omega_{TAE}) < 0.1$ characterisitc of DKAE modes. The frequency does not reproduce the usual AEs scaling and increases in time until the mode saturates in the TAE frequency range. The energetic character [12, 13] of the modes may also play a role. A comparison with a global gyrokinetic model accounting for both the drifts- and the energetic character is necessary to properly identify these modes.
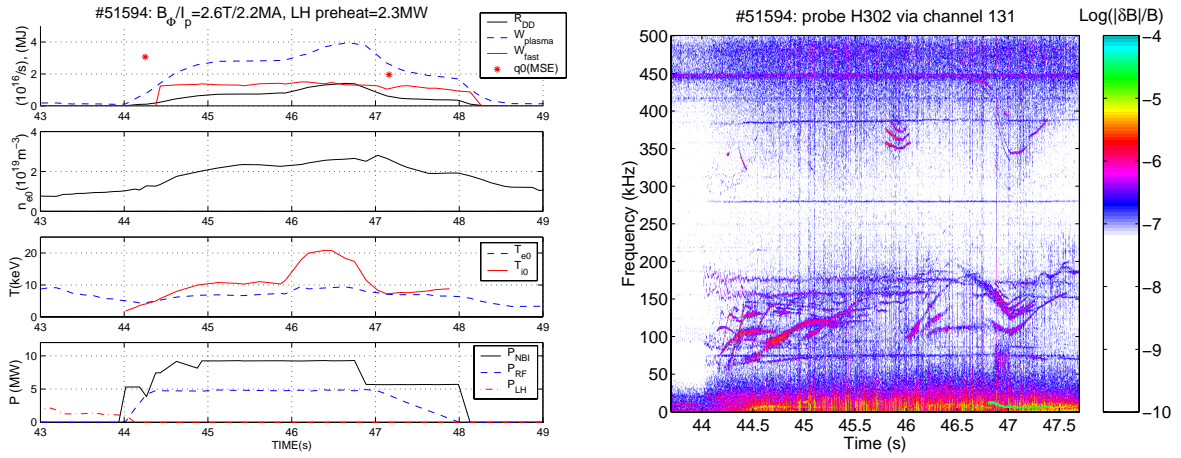
Figure 2: Instabilities are observed in the shear-optimized JET discharge 51594 using passive measurements of magnetic fluctuations.

3. Drift-kinetic Alfvén instabilities predicted in NSTX

Low aspect ratio plasmas differ in several manners from conventional ones and it is useful to address what could be the limits of applicability of the PENN model to such configurations. The most obvious limit is the strongly shaped toroidal geometry (in this NSTX model equilibrium, a tight aspect ratio R/a=1.3, elongation b/a=1.9, q_0=0.85, q_{95}=4), which yields strongly toroidal modes that are particularly well represented with the 2D finite elements discretization in configuration space. The large magnetic compressibility $\vec{B}_\parallel = \nabla \times \vec{A}_\perp$ associated with the bulk pressure (β=23%, β_p=0.37) is taken into account using four potentials $(\vec{A}, \Phi)$ instead of the two components $(A_\parallel, \Phi)$ that are often sufficient to model AEs in conventional tokamaks. The large bulk ion Larmor radius ($\rho_D/a \simeq 0.02$) and the large drift frequency $\omega_{*D}/\omega_{TAE} > 1$ resulting from rather energetic thermal particles in a low magnetic field (T_e=2.7 keV, T_i= 1 keV, B_0=0.3 T) are likely to cause strong effects from the finite Larmor radius and the equilibrium inhomogeneities; both are taken into account in the PENN code, which assumes here an approximative functional dependence $k_\parallel = 1/(2qR)$ for the resonant wave-particle interaction. This provides a good qualitative description of the mode conversion between the fluid, kinetic Alfvén and drift wavefields, but may not always be sufficient for a quantitative evaluation of the drift-wave damping. The stability predictions below will need to be verified with a more complete model for macro-instabilities [4]. Because of the tight aspect ratio, a significant proportion of the particles are trapped and do not provide resonant interactions; it was suggested that collisional damping of trapped electrons become important instead. The power transfer to passing drift-kinetic electrons P_{DKe} [14] has therefore been supplemented with the collisional damping of trapped electrons

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

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

where $\nu = (\nu_{ee} + \nu_{ei})R/\rho$ is an effective collision frequency and Φ is the electrostatic potential.

The power transfer with fast- and bulk ions is evaluated using the non-local expressions from Ref.[15] that are valid to all orders in the Larmor radius.
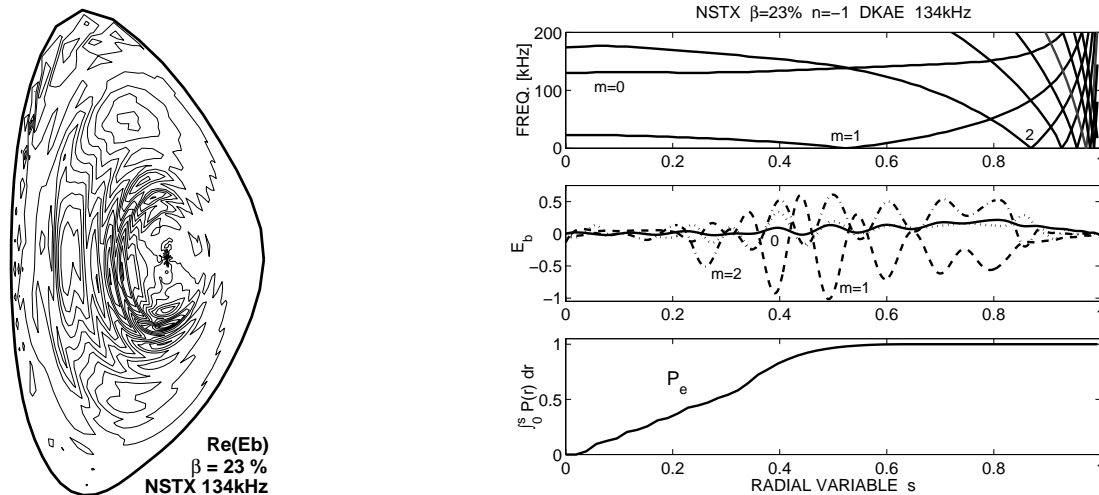

Figure 3: In NSTX, a global $n = 1$ DKAE at 134 kHz with a very weak damping $|\gamma/\omega| = 0.003$ is expected to becomes unstable already for moderate beam pressure gradients.

Weakly damped DKAEs susceptible to become unstable with a moderate drive from fast or even thermal ions are found both in the TAE and EAE frequency range. Figure 3 illustrates how a global n=-1 mode is formed at 134 kHz by elliptical coupling of the m=0,2 shear-Alfvén wavefield components. Mode conversion occurs to a kinetic-Alfvén wave, which propagates across the magnetic field and is responsible for the short radial oscillations that are visible on $E_b(s)$. Because of the large ratio ω_{*D}/ω_{TAE}, the largest component is an m=1 drift-wave induced by mode conversion in the neighborhood of the q=1 rational surface where $k_{\parallel} = R^{-1}(n + m/q) \approx 0$. The large compressibility $B_{\parallel} \simeq B_{\perp}$ results from the high plasma β. Power transfers from the particle to the wavefield integrated from the center $\int_0^s (P_e + P_D)dr$ show that resonant interactions with passing electrons provide for most of the small global damping $|\gamma/\omega| = 0.003$ in the plasma core $s < 0.5$. Towards the edge, most particles are trapped and neither the Landau damping nor the collisional damping significantly contribute to damp the short wavelengths oscillations that are mode converted in the high magnetic shear divertor region (clearly visible on the high field side of the torus).

Non-local calculations of the energetic particles drive have been performed assuming a relatively peaked density in the core. They indicate that DKAEs become unstable already for moderate beam pressures $\beta_b > 2\%$. Large magnetic fluctuations from the helicity injection could also excite weakly damped (but stable) DKAEs that could play a role in the global drift-Alfvén turbulence.

4. Implications for ITER and outstanding issues

Studies using (EDA, FEAT) model equilibria predict that conventional scenarii with monotonic or nearly flat safety factor profiles exist where all the AEs with low to intermediate mode numbers are stable [15]. Shear reversal in a reactor with a large safety factor on axis $q_0 > 2.5$, however, again brings the TAE frequency down into the drift frequency range and the PENN predictions in Ref.[11] show that global DKAE instabilities could appear above an intolerably small $\alpha-$particle pressure gradient. More work with an improved modeling and comparisons with experimental data are necessary to establish an understanding of the linear mode conversion involving electro-magnetic drift waves and hopefully identify high performance regimes where also the global DKAEs are stable. At present, the knowledge of the non-linear evolution and the associated transport stems almost exclusively from experiments and is not sufficiently established to draw firm conclusions for a reactor.

References

[1] A. Fasoli *et al.*, Phys. Plasmas 5 (2000) 1816

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

[3] A. Fasoli *et al.*, this conference

[4] A. Jaun, J. Vaclavik, *Theory of Fusion Plasmas* (Proc. Int. Workshop, Varenna, 2000) Editrice Compositori, Bologna (2000)

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

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

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

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

[9] H.H. Duong *et al.*, Nucl. Fusion 33 (1993) 749

[10] C. Challis *et al.*, "Effect of q-profile Modifications by LHCD on Internal Transport Barriers in JET", Plasma Phys. Contr. Fusion (2000) submitted

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

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

[13] F. Zonca, L. Chen, R.A. Santoro, J.Q. Dong, Plasma Phys. Control. Fusion 40 (1998) 2009

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

[15] A. Jaun, A. Fasoli, J. Vaclavik, L. Villard, Nucl. Fusion 11Y (1999) 2095