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Stability of Alfvén Eigenmodes in Optimized Tokamaks[*]

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Abstract. Alfvén eigenmodes (AEs) with intermediate toroidal mode numbers are modeled using the global gyrokinetic PENN code to determine the stability of high performance tokamak discharges in the presence of energetic particles. A large plasma pressure and a weak magnetic shear in the core give rise to radially extended kinetic AEs, which are stabilized by the high shear at the edge of a divertor (X-point) configuration. Large values for the safety factor and the ion Larmor radius in reversed shear operation may however trigger drift-kinetic Alfvén eigenmodes (DKAE) instabilities that could affect the alpha-particle confinement in a reactor.

Subject classification code: D0Tt

1 Introduction

To develop an economically attractive design for a tokamak reactor, a complicated optimization procedure is needed to achieve a stable configuration with sufficiently good confinement properties. The major radius R, toroidal magnetic field B and plasma current I_p have to be chosen as small as possible, in an equilibrium that maximizes the normalized kinetic pressure $\beta = 8\pi P/B^2$ and the fusion yield. Experiments suggest that the heat transport can be strongly reduced by inverting the safety factor profile $q(r)$ in the plasma core [1]. It is therefore important to determine how the pressure and the magnetic shear $\hat{s} = \frac{r}{q}\frac{\partial q}{\partial r}$ affect a range of instabilities that ultimately limit the plasma performance.

In a reactor, Alfvén eigenmodes (AEs) can potentially be driven unstable by the $\alpha-$particle pressure gradient and affect the global confinement. The regimes where this may occur can not be explored with dimensionless experimental scalings using the tokamaks currently in operation. Numerical models such as the PENN code [2] are therefore needed to make predictions [3] and, to be credible, need to be validated against existing experimental measurements [4, 5]. Having previously tested how the global AE damping rate varies with the edge magnetic shear ($|\gamma/\omega| \simeq 0.02 - 0.08$) [6] and correctly predicted a decrease of the damping with the isotope mass by mode-conversion in the core ($|\gamma/\omega| \simeq 0.02 - 0.01$) [7], a validation is further required for the non-local power transfer model introduced in Ref.[3] to compute the fast particle drive.

We therefore start by discussing measurements from the Joint European Torus (JET) in section 2, showing that AE instabilities disappear when β rises without any reduction of the fast particle pressure. This observation is interpreted theoretically with a gyrokinetic model, showing what happens to AEs when the pressure becomes large in a hot plasma. The current is then artificially reduced in the core to study in sect.3 how the AE stability is affected by changing the sign of the magnetic shear. The choice of a strongly reversed configuration for an international tokamak experimental reactor (ITER) [8] illustrates how drift-kinetic Alfvén eigenmodes (DKAE) [9] can be driven unstable when the TAE frequency is brought down into the ion-drift range with large values of the safety factor in the core. Section 5 concludes the paper and summarizes the most important results.

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2 Rising the bulk pressure

Different terms contribute to the total pressure $P_{tot} = \sum n_j T_j + P_{fast}$ and can affect the AE stability computed with a gyrokinetic plasma model. The MHD equilibrium pressure results in a Shafranov shift of the magnetic axis, alters the shear-Alfvén gap structure and increases the magnetic compressibility of the wavefield. The species densities n_j modify the Alfvén frequency through the ion inertia $n_i m_i$; the electron temperature T_e and the finite Larmor radius (FLR) of the bulk ions ρ_i change the mode-conversion efficiency, the kinetic-Alfvén wavelength and the Landau damping.

Rather than studying a parameter space that is far too big to be explored systematically, we choose here to analyze the evolution of a specific JET discharge (shot 40308). It is a typical hot-ion H-mode deuterium plasma with parameters and profiles very similar to the values obtained during the record fusion power discharge 42677 where no AE instability was observed. Fig.1 shows the time evolution of the spectrum of magnetic fluctuations recorded by a magnetic coil at the edge. Unstable AEs with toroidal mode numbers $|n| = 6 - 11$ clearly disappear from the measurements around $t = 13.0$ sec and require an explanation. Three time slices at $t = 12.04, 12.57, 13.10$ sec labelled (a), (b) and (c) are reconstructed from the experimental diagnostics [10, 11], following the evolution of the single-null magnetic equilibrium with a safety factor q_0 =0.76, 0.81, 0.84, q_{95} =3.2, 3.3, 3.5, internal inductance l_i =1.07, 0.99,0. 94 and a rising pressure β =0.15, 1.3, 2.4%, β_p =0.05, 0.41, 0.78, n_{e0} =1.4, 2.6, 3.5 $\times 10^{19}$ m^{-3}, T_{e0} =6.8, 9.4, 11.3 keV, T_{D0} =14.0, 22.5, 24.9 keV. After $t = 12.0$ sec (a), neutral beam P_{NBI}(140 keV)= 10 MW, P_{NBI}(80 keV)= 8 MW and ion-cyclotron $P_{ICRF} = 4.5$ MW power is injected and provides for a non-decreasing fast particle drive until a giant edge-localized mode (ELM) destroys the confinement around $t = 13.45$ sec.

The global AE stability is analyzed with the gyrokinetic **PENN** code [2], using a second order FLR expansion to model the global dielectric response of the plasma [12] with a wave vector parallel to the magnetic field $k_{\|} = (2qR)^{-1}$ assumed for the Landau damping from the bulk species. The power transfer between the wavefield and the particles is evaluated using a drift-kinetic model for the electrons [13] and a full-non local model valid to all orders in the Larmor radius for the ions [3]. A slowing-down distribution models the fast particles with a birth energy of 140 keV and a radially peaked profile $n_f(s) = n_{f,0}(1 - s^2)^{15}$, where $s = \sqrt{\psi}$ is the normalized radius measured in terms of the square-root of the poloidal magnetic flux ψ.

Figure 2(a) shows that the wavefield of the most unstable kinetic Alfvén eigenmode (KAE) with a toroidal mode number $n = -6$ and dominant Fourier components $m = (5, 6)$ is initially localized in the plasma core $s \simeq 0.2 - 0.4$. The volume integrated power transfer from the fast particles to the global wavefield (energetic particle drive) is exactly balanced by the absorption from the bulk species (mainly electron Landau damping) for a critical fast particle pressure $\beta_{f,crit}^{(a)} = 4 \times 10^{-4}$ considerably lower than the value $\beta_{f,exp} \simeq 2 - 5 \times 10^{-3}$ estimated to be present in the experiment. This is in good agreement with the observation of an instability at the beginning of Fig.1.

As both NBI and ICRF deposit power in the plasma and increase the fast particle pressure in the core, the bulk temperatures also rise together with the normalized MHD pressure. Figure 2(b,c) illustrate how the wavefield becomes increasingly global as new mode-conversion layers appear in the vicinity of toroidal gaps, located around s =0.32, 0.54, 0.67, 0.72, 0.78, 0.82, 0.87, 0.89, 0.91, etc in Fig.2(c). The toroidal coupling of individual kinetic-Alfvén wave Fourier components yields a relatively high n and very global mode, which could not be described within the ballooning approximation commonly used for high toroidal mode numbers. Similarly to the low n KAEs, which get strongly damped when they reach the high magnetic shear region associated with an X-point [6], mode-conversion occurs to a kinetic-Alfvén wave and becomes visible at the bottom of Fig.2(c). Strong electron Landau damping raises the fast particle marginal stability pressure first to $\beta_{f,crit}^{(b)} = 3 \times 10^{-3}$ and later to $\beta_{f,crit}^{(c)} > 0.01$ so that the KAE simply disappears from the measurements when the Landau damping from the edge exceeds the fast particle drive in the core.

Even though it is only indirectly linked with the stabilization observed in the experiment, the power balance in the plasma core deserves some extra attention. Fluid models predict that core-localized TAE modes [14] get more and more peaked and therefore Landau damped by the electrons until they finally disappear in the lower continuum around t =13.0 sec [15]. In the gyrokinetic model, the peaking of the wavefield and the Landau damping are however limited because the shortest scalelength is dictated by the bulk ion gyro-radius. The instability is driven by resonant interactions with the kinetic-Alfvén wave and the KAEs would remain unstable in the absence of the strong damping from the edge. Without the stabilizing contribution from the axis or the divertor (X-point), rather global KAE instabilities with intermediate toroidal mode numbers could therefore survive in a reactor for appreciable values of β. Caution is necessary for the interpretation of Fig.2(c), where the kinetic-Alfvén wave converted near the axis ($s < 0.1$) does not *a posteriori* satisfy the FLR expansion condition for the bulk ions $k_\perp \rho_D < 1$. This affects locally the short wavelengths, the mode-conversion assuming a poloidal wave number $m \simeq nq$, we obtain the ratio

$$\frac{\omega_*}{\omega_{TAE}} \simeq 2nq^2 \left(\frac{\rho}{a}\right)^2 \left(\frac{R\omega_{pi}}{c}\right) \qquad (1)$$

where ρ/a is the bulk ion Larmor radius normalized to the minor plasma radius, ω_{pi} the ion plasma frequency and c the speed of light. The drift character of the wavefield gets more pronounced when ω_*/ω_{TAE} approaches unity; by reducing the magnitude of the magnetic field at low $q \simeq 1$ in the DIII-D tokamak, it was however found to be important already for values as low as $\omega_*/\omega_{TAE} \simeq 0.05$.

The following study illustrates what happens if a high safety factor in the core reaches $q_0 = 4.5$ with a deep shear reversal out to $s(q_{min}) = 0.78$ where $q_{min} = 3.77$, in a scenario examined for an optimized ITER design ($R_0 = 6.2$m, $B_0 = 5.5$T, $I_p = 8$MA, $a/R = 2.5$, $l_i = 0.38$, $n_e = 7 \times 10^{19}\text{m}^{-3}$, $T_e = 35$keV, $T_{DT} = 30$keV). Given the large safety factor $q \simeq 4$ and the large value of $\omega_*/\omega_{TAE} \simeq 0.01n$, it is not surprising that the $n = -3$ DKAE at 53 kHz illustrated in Fig.4 has a strong kinetic- and a drift- character. Because of the large radial $ak_\rho/(2\pi) \in [-6; 6]$ and poloidal $m \in [-15; 15]$ mode numbers and the high order of the interactions $l \in [-4; 4]$, the stability analysis remains close to the limit of the numerical convergence. The fast particle pressure at marginal stability can however be estimated to be $\beta_{f,crit} < 10^{-3}$, which is well below the limit tolerated in a burning plasma.

Rather dramatic effects were observed on the fast particle confinement during AE activity in DIII-D [17]. The theoretical understanding of these global drift-wave instabilities is however still limited, restricted mainly to a study involving DKAE modes where the drift wave is damped by the bulk species and driven by the fast particles [9] and a study for Alfvén-ion temperature gradient (AITG) modes that are driven by the bulk species even without the presence of fast particles [18]. More work is required on both fronts to develop a physical understanding of the instabilities and require new comparisons with experiments. With the present knowledge, it is however advisable to avoid planning reactors that exceed $\omega_*/\omega_{TAE} \simeq 0.002n$, to remain in a regime where little degradation of the fast particle confinement has been observed experimentally in JET.

5 Summary

Three studies examined how the stability of kinetic AEs is affected when a tokamak plasma is optimized for large values of β, a reversed magnetic shear and a large safety factor in the core. The pressure and the magnetic shear modify the spatial scales of the global fluid wavefield and the kinetic-Alfvén wave, allowing mode-conversion to take place where both scale lengths match. For KAEs with intermediate toroidal mode numbers studied in this paper ($|n| = 6$), this is possible:

1. in a succession of toroidicity gaps, which get radially coupled as β rises and result in strongly kinetic and global KAEs,
2. in the plasma edge, where the large magnetic shear associated with the plasma shaping (X-point) squeezes the fluid wavefield radially and yields a strong global damping rate comparable to the one predicted for low n AEs [6],
3. near the plasma center where the aspect ratio is large and the shear sufficiently weak that the kinetic-Alfvén wave can expand radially,
4. for large values of nq leading to short poloidal wavelengths with multiple mode-conversion regions that interact to form a strongly kinetic mode. This becomes particularly important when $\omega_*/\omega_{TAE} \simeq 2nq^2(\rho/a)^2(R\omega_{pi}/c)$ approaches unity and drift-kinetic Alfvén eigenmodes (DKAE) become unstable.
5. Mode-conversion at Alfvén resonances is generally not very efficient, making shear-Alfvén gap structures a poor indicator to predict the damping or even guess the existence of AEs.

The global stability of an AE is ultimately determined from the balance between the fast particle pressure gradient drive and the Landau damping from mainly the electrons. This has in general to be evaluated numerically with tools such as the PENN code. In the presence of a strong damping provided by the high edge magnetic shear in a diverted plasma (X-point), it is however possible to say that a large bulk β and a weak central magnetic shear are both stabilizing as they make the perturbations more global. Deep shear reversal resulting in large values of the safety factor should be avoided to keep ω_*/ω_{TAE} low enough to prevent the appearance of DKAE instabilities.

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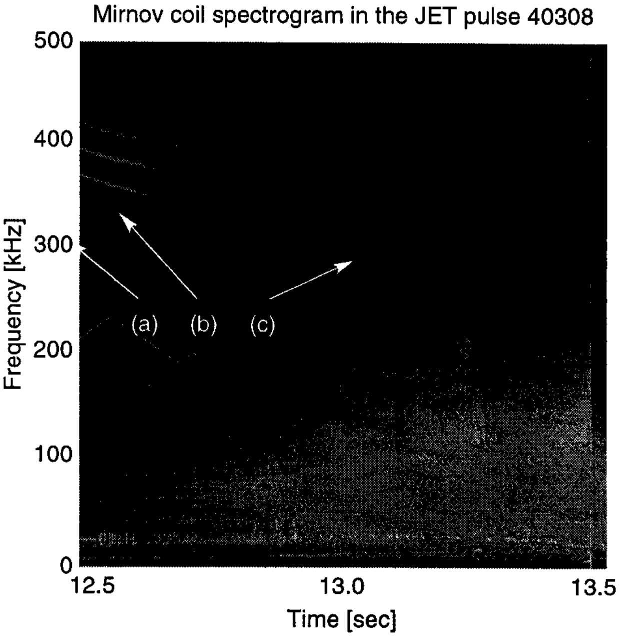

Figure 1: Magnetic perturbation $\log(|\delta B/B|)$ measured by external Mirnov coils in the high performance deuterium JET discharge 40308. Unstable AEs with toroidal mode numbers $n = 6-11$ and amplitudes $\delta B/B \simeq 10^{-7}$ disappear despite a rising drive. The labels (a-c) refer to the three time slices at $t = 12.04, 12.57, 13.10$ sec examined theoretically in Fig.2.

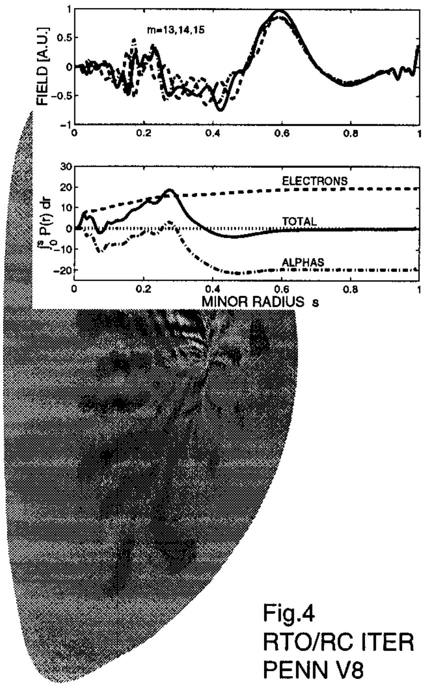

Fig.4
RTO/RC ITER
PENN V8

Figure 4: Strongly unstable $n = 3$ drift-kinetic Alfvén eigenmode (DKAE) at 53 kHz predicted for an optimized reactor with a deeply reversed magnetic shear and a large safety factor $q_0 = 4.5$. The critical fast particle pressure for marginal stability here is $\beta_{f,crit} < 1 \times 10^{-3}$.