Collective Modes and Fast Particle Confinement in ITER

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Abstract. The results of numerical models have been compared to the existing data to investigate damping mechanisms, check parametric dependencies and extrapolate the existing experimental results to reactor conditions that remain inaccessible to present day tokamaks. Stabilising mechanisms involving mode conversion to kinetic Alfvén waves have been identified. The comparison between theory and experiment suggests that the limit above which the alpha particle pressure starts giving rise to instabilities that can degrade the plasma performance is much higher in conventional burn scenarios than in reversed shear configurations.

1. Introduction

Ions in the MeV energy range are generated as α-particles by DT fusion reactions, and can be created by additional heating, such as ICRH on the fuel ions. To confine the heat and sustain the burn, fast particles need to transfer their energy to the bulk species, for example by collisions with electrons. Instabilities and toroidal magnetic field inhomogeneities may prevent this and, through sudden losses of confinement, could damage the first wall. Models identified the key stabilizing mechanisms as the mode conversion to a kinetic Alfvén wave triggered by strong edge magnetic shear / weak central shear [1] and a mode coupling within a toroidicity gap that has sometimes been approximated as radiative damping [2]. These models have to reproduce the parametric dependencies in present day tokamaks to make credible extrapolations for a reactor.

2. Good stability in conventional scenarios with a high edge magnetic shear

Experiments in the Joint European Torus (JET) measured the damping rate of Alfvén Eigenmodes (AE) with low toroidal mode numbers n=0-2; the data shows that the stability of a limiter plasma increases with the shaping [3] and decreases with the bulk plasma β [4]. Fig.1 illustrates the first case with the damping rate of an $n = 1$ TAE mode measured as a function of the elongation and the triangularity of the plasma edge ($B = 2.2$T, $q_0 \approx 0.9, q_{95} \approx 4$, $n_{e0} = 2.5 \cdot 10^{19}\mathrm{m}^{-3}$, $T_{e0} \approx 2.5$keV). The damping rate rises linearly with the shaping parameters, with a sharp increase when the elongation exceeds $\kappa > 1.35$. This strong sensitivity of the AE damping rates upon the shape and the magnetic shear at the plasma edge suggests a method to control the stability of fast ions resonating with radially extended AEs. Together with the large number of measurements made in conventional diverted plasmas [5], these new studies confirm the strong stabilizing effect of the high magnetic shear at the plasma edge, which has previously been predicted for radially extended modes from low [1] to intermediate mode numbers [6] and applies also to conventional ITER scenarios [7].

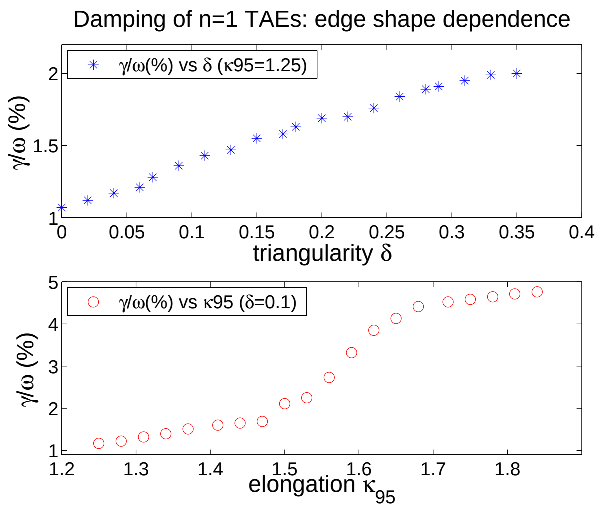

Fig 1. Damping rate of global n=1 AE modes measured as a function of the elongation κ and the triangularity δ in JET limiter plasmas.

Limiter configurations with a small edge magnetic shear have been used to study the physical dependencies of weaker damping mechanisms that are expected to become dominant when the AEs are radially localized [8, 9]. They show that the radiative damping model from ideal-MHD codes fails to reproduce the order of magnitude and the trend in the data, suggesting that a more complete gyrokinetic description of toroidal mode conversion mechanisms is required to predict the AE stability.

All together, these studies confirm earlier predictions for conventional ITER plasmas, showing that radially extended TAE modes should be stable and that conventional reactor conditions exist where fast particle losses due to Alfénic instabilities should be small.

3. Alfvénic instabilities could set an upper limit for shear reversal

Drift-kinetic AE instabilities have been predicted to occur in deeply reversed shear configuration in ITER [6]. Low n (n=3-5) instabilities have been observed in the 50 kHz frequency range in JET diverted discharges in which the ratio between the ion drift and the AE frequency ratio $\omega_*/\omega_{TAE} \simeq 2nq^2(\rho/a)^2(R\omega_{pi}/c)$ is large. The measurements in Fig.2 show that unstable modes appear even without ICRF driven MeV energy ions with a low beam to Alfvén velocity ratio $v_{\|NBI} \approx 0.3v_A$; they subsist in a diverted plasma and do not follow the scaling expected for Alfvén waves. The observed modes could be related with drift-kinetic AEs, although no clear identification of their nature was possible to date.

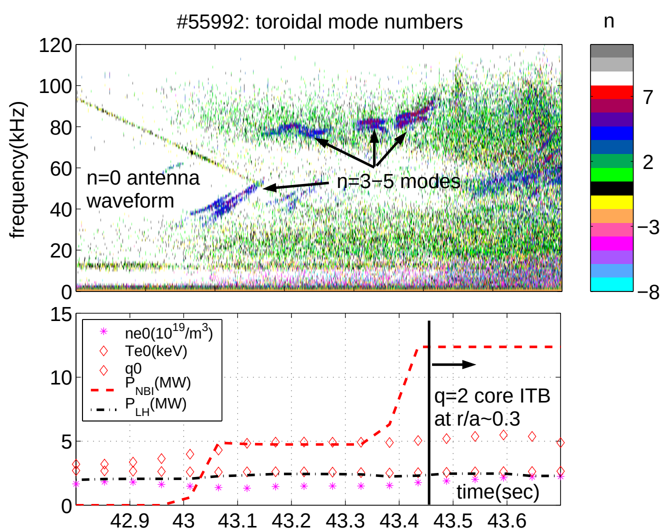

Fig.2. Unstable n=3-5 modes in a deep reversed shear plasma do not follow an Alfvénic scaling.

In the presence of high energy NNBI and ICRH ions, frequency sweeping instabilities have been detected in the JT-60U and JET tokamaks [10, 11, 12]. Instabilities observed during beam heating in the DIII-D tokamak have been analyzed with a high-n code that treats the beam-ion distribution non-perturbatively. The analysis suggests that two types of energetic particle modes are destabilized: the resonant TAE and the resonant kinetic ballooning mode [13, 14].

More work is however required to develop and validate theoretical models, before adequate predictions can be made for the stability boundaries in reversed shear ITER configurations.

4. Non-linear dynamics and fast-particle transport.

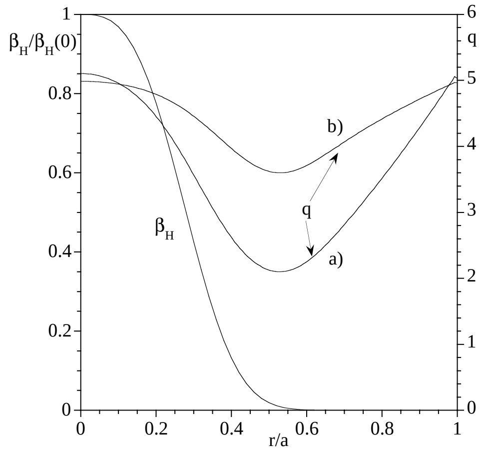

Fig.3: Equilibrium fast-particle normalized pressure and q-profiles that are used in the present simulations with the HMGC code [18].

Tokamak plasma equilibria with hollow q-profile can lead to improved confinement regimes. These regimes are generally optimised with respect to the overall plasma performance, leading to conditions that may not be ideal in terms of the stability of fast particle driven modes. It is therefore of crucial importance to investigate fast particle nonlinear dynamics and transport in these regimes.

The improved confinement region of the plasma is included within the minimum-q surface, where the fast-particle pressure is the largest and Energetic Particle Modes [15] (EPM) are most likely excited [16]. We analyze EPM non-linear dynamics with respect both to saturation mechanisms and energetic particle transport assuming a fast particle energy density β_H with a peaking factor $\beta_H(0)/<\beta_H>$=9.2 and the two different q profiles of Fig.3 [17].

Simulations results are obtained with the Hybrid MHD Gyrokinetic code HMGC [18] assuming plasma equilibria with shifted circular magnetic surfaces. The velocity space distribution function of energetic ions is an isotropic Maxwellian with flat temperature profile. Other fixed parameters are $a/R_0 = 0.1$, ρ_H/a=0.01 (normalized energetic ion Larmor radius), $v_H/v_A|_{r=0} = 1$ (energetic ion thermal speed normalized to the Alfvén velocity, on-axis value). Both the energetic and the thermal ion species are assumed to have the same mass number. Fig. 4 presents the results relative to the q profile (a) in Fig. 3 and $\beta_H(0) = 0.025$. A radially constant thermal-plasma density is assumed, corresponding approximatively to a radially constant Alfvén velocity. We note that an unstable EPM [15], is excited inside the upper continuum (top) by the resonant interaction with energetic ions. Its saturation takes place because of a strong, convective, radial displacement of the energetic ions. The maximum of the power spectrum then migrates in frequency towards the toroidal gap and radially outwards. This can be understood as follows. The mode forms as the best compromise between maximizing the drive and minimizing continuum damping. Such a compromise is reached by following the outward-moving β_H maximum gradient and properly adjusting the mode frequency. Once the gap is reached (bottom), the mode occupies the most favorable location and extension consistent

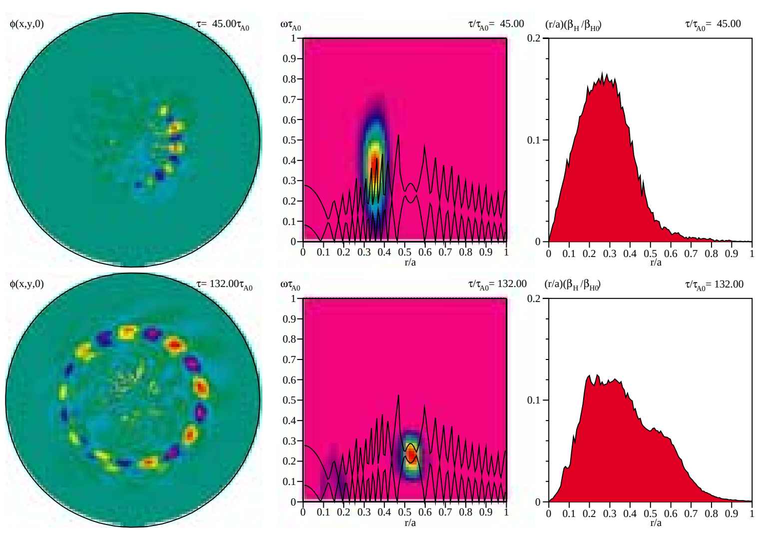

Fig 4: Contour plot of the scalar potential ϕ at a fixed toroidal angle (left), power spectrum $\sum_m |\phi_{m,n}(r,\omega)|^2$ in the $(r/a, \omega\tau_{A0})$ plane (center) and energetic-ion line pressure profile, $(r/a)\beta_H(r)/\beta_H(0)$ (right), at two different times: linear growth phase (top; $\tau = 45\tau_{A0}$) and saturated phase (bottom; $\tau = 132\tau_{A0}$). Here, $\tau_{A0} = R_0/v_A|_{r=0}$. The q profile (a), radially constant thermal-plasma density and $\beta_H(0) = 0.025$ have been assumed.

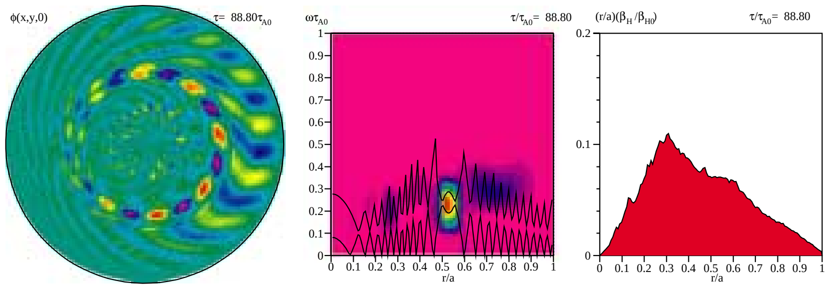

Fig. 5: Saturated phase for $\beta_H(0) = 0.05$ and the rest as in Fig. 4.

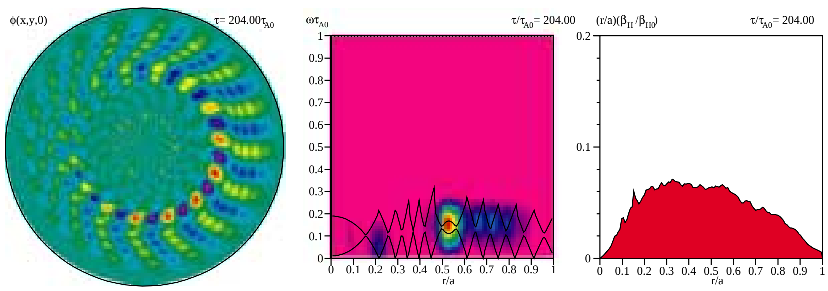

Fig. 6: Saturated phase for the q profile (b) of Fig. 3, rest as in Fig. 4.

with the radially displaced energetic ion free energy source. This corresponds to a localization around the minimum-q surface [17].

According to the above results, the non-linear EPM dynamics corresponds to the radial displacement of an unstable propagating front (avalanche), associated with rapid fast-particle radial redistribution which stop at the minimum-q surface [17]. These facts suggest the idea of an energetic-particle Internal Transport Barrier (ITB), analogous to that of the thermal plasma. The robustness of the barrier can be seen in Fig. 5, where the time-asymptotic energetic particle radial distribution is not significantly altered for the q profile (a) in Fig. 3 and $\beta_H(0) = 0.05$. In fact, the time-asymptotic fraction of energetic particles confined within the minimum-q surface, which at equilibrium is 99.8% (cf. Fig. 3), is 79% in the case of Fig. 4 and 65% in that of Fig. 5. The global particle losses in the two cases are, respectively, 1.3% and 3.1%, indicating that particle transport results mainly in radial particle redistribution. The properties of the fast-ion ITB crucially depend on the q profile [17]. Fig. 6, in fact, shows the simulation results in the saturation phase for the q profile (b) of Fig. 3 and the other parameters as in Fig. 4. The detrimental effect on the energetic ion confinement is macroscopic, with global particle losses of 6.6%, and the time-asymptotic fraction of fast-ions confined within the minimum-q surface is 56%. These results demonstrate that the shape of the q profile determines the Alfvén mode behavior, as it affects both the toroidal gap and the resonant-excitation frequencies, the size of the energetic-ion orbits, the radial extension and the toroidal coupling of the different poloidal harmonics as well as the energetic-ion drive intensity, estimated by the quantity $\alpha_H \equiv -R_0 q^2 \beta_H'$. Simulations clearly indicate that profiles with lowest q_{min} (above $q_{min} = 2$ for MHD stability reasons) and highest q'' exhibit the best transport properties of fast ions [17].

The reason for this is that, for a given value of β_H', the mode radial width scales, near the q_{min} surface, as $1/\sqrt{nq''}$, while the typical orbit size is proportional to q_{min}. Decreasing the hollowness of the q profile, for fixed $q(0)$ and $q(a)$, yields lower q'' and larger q_{min} values, and makes both the mode and the orbit widths larger than in the deeply-hollow q-profile case. Moreover, the energetic-ion drive intensity, scales as q_{min}^2. The mode is then a more efficient scattering source for energetic-ion orbits even in the relatively low β_H case ($\beta_H(0) = 0.025$).

The present work addresses the issue of self-consistent EPM non-linear dynamics and fast-particle transport in hollow-q profile tokamak equilibria [17], and the results presented here have clear implications on the choice of current profiles in a burning plasma, suggesting that good confinement of fusion products will set a limit on the maximum radial location of the minimum-q surface and on the value of q_{min}.

5. Ripple-induced losses

Ferritic steel (FS) inserts are considered as a measure to reduce the amplitude of the toroidal magnetic field (TF) ripple and the loss of energetic particles that could occur in reversed shear plasmas. Two independent calculations have been carried out [19, 20] using models for the energetic particle orbits including the effect of scattering by the TF ripple and Coulomb collisions. The results demonstrate that an optimal arrangement of FS inserts reduces the alpha particle losses by one order of magnitude or more, with a power loss well below 1% when $q_{\min} < 3$. Fig.7 depicts the heat deposition on the first wall due to ripple losses for a reversed shear plasma with $q_{\min} = 2$ and a fusion power of 500 MW, showing that the heat flux should be much lower than the design parameters of the first wall (0.5 MW/m2) when FS inserts are installed [20]. The calculations show that with FS inserts, the operation is possible for a wide range of current profiles and magnetic fields.

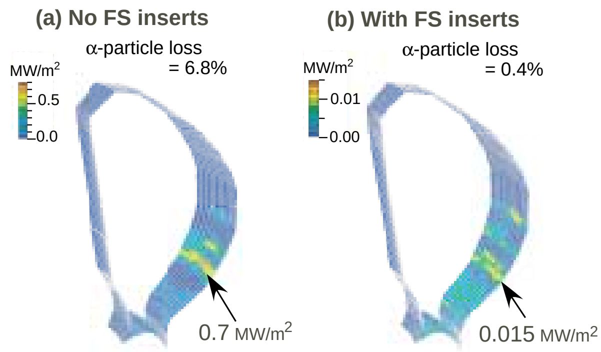

Fig. 7: Heat deposition on the wall between the neighboring coils in ITER. (a) Original TF ripple and (b) the reduced ripple with FS inserts.

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