Evolution of Fast Particle Driven MHD Instabilities for the ITER 15MA Scenario

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1. Introduction

The present studies are carried out in the frame of the high priority tasks of the ITPA Energetic Particles Topical Group and can be compared with similar studies being performed with the MEGA [1] and the HAGIS-LIGKA [2] codes. Our simulations extend the fast particle driven MHD stability analysis, performed recently for the steady-state ITER case [3] to the ITER Q = 10 15MA scenario.

The spatial structure of toroidal Alfven eigenmodes (TAE) $\eta_{mn}(F_p)$ has been calculated with the KINX code [4], (F_p and s are normalised poloidal and toroidal flux functions). The fast particle nonlinear dynamics, TAE growth rates and wave saturation levels are computed with the VENUS+δf [5] orbit following code. Fourier decomposition in Boozer coordinates (s, θ, ζ) of the TAE mode with a poloidal, toroidal indices m,n and mode frequency ω has a form $\xi^s = A(t)\ \Sigma\ \eta_{mn}(s)\ \cos(m\theta - n\zeta - \omega t)$. The evolution of the TAE amplitude $A(t)$ is described from the equation for the fast particle-wave interaction

$$dA/dt = -<\int Z\, e\, \delta f\, \boldsymbol{V}\cdot\boldsymbol{E}\, d\tau > / \, (2K\,\omega^2 A) - A\,\gamma_d, \qquad (1)$$

here $K = \int\rho_b\, \xi^2\, dV$ is the kinetic energy of the plasma perturbation, $\rho_b = m_b\, n_b$ the mass density of the bulk plasma, dV the volume unit, $d\tau = d^3x\, d^3V$ the phase volume unit, $Z{\cdot}e$ the particle charge, δf the perturbed distribution function of fast particles, $\boldsymbol{V}$ the particle velocity vector and $\boldsymbol{E}$ the wave electric field. The ion Landau damping rate γ_d is obtained from analytic estimates [6] and included into the VENUS code. The TAE growth rate γ is computed from $\gamma = dA/(Adt)$, and the radial component of the TAE perturbation $\delta\boldsymbol{B} = \mathrm{rot}\alpha\boldsymbol{B}$, normalized to the central magnetic field B_0, is defined as

$$\delta B_r/B_0 = \delta\boldsymbol{B}\,\nabla s/[|\nabla s|B_0] = -\mu_0(I\partial\alpha/\partial\theta + J\partial\alpha/\partial\zeta)/[|\nabla s|g^{1/2}\, B_0], \qquad (2)$$

where J and I are the toroidal and poloidal current flux functions and $g^{1/2}$ is a Boozer jacobian.

2. Simulation results for the ITER 15MA Q =10 scenario

Plasma parameters and profiles predicted by the ASTRA code for the ITER Q = 10 with plasma current of 15MA and monotonic q profile with $q(0) = 1.0$ are described in [1], [2], [6], [7]. At mid-radius, where the drive of alpha-particles and NBI-produced ions is expected to exceed the damping, different TAE modes were explored. Global Alfvenic modes with $n \approx 20$ have found to be amongst the most unstable fast ion driven modes and are the focus of the work in this paper. The plasma cross-section with this perturbation is shown in Fig. 1. Fig. 2(a) shows the profiles of the components of the ballooning TAE mode computed with the KINX code with poloidal indices $m = 20$ (brown), $m = 21$ (blue) with a mode frequency of ω = 71 kHz and the safety factor (black). Fig. 2(b) shows the components of the antiballooning mode with a mode frequency of ω = 106 kHz for the same poloidal indices.

Fig. 3 shows the nonlinear saturation of the ballooning $n = 20$ TAE mode amplitude driven by α-particles with the VENUS code for the ITER Q = 10 scenario without any damping mechanisms. The initial linear normalized growth rate of $\gamma/\omega = 0.4$ (red squares) is high due to the large central α-particle density of $9.26\text{x}10^{17}$ m^{-3}, which leads to a high amplitude of the perturbation in the range of $\delta B_r/B \approx 10^{-3} - 10^{-2}$ (blue circles) similar to HAGIS results [2].

Different damping mechanisms for the ITER Q = 10 scenario have been considered analytically in [6]. For mid-plasma radius the thermal ion Landau normalized damping is equal to $\gamma_d/\omega = 0.005$, continuum damping is equal to $\gamma_d/\omega = 0.02$ and the radiative and the electron collisional damping are small and can be neglected. From the VENUS simulations, a normalized damping of $\gamma_d/\omega = 0.2$ is required to decrease the ballooning mode saturation level by a factor of 2 with respect to the non-damped case (blue circles on Fig.4) and thus no significant damping effect is expected for this mode in the ITER Q = 10 plasma conditions.

Fig. 5 shows the nonlinear saturation of the antiballooning $n = 20$ TAE mode amplitude (blue circles) computed with the VENUS code without any damping mechanisms. The linear normalized growth rate of $\gamma/\omega = 0.8$ (red squares) for the antiballooning mode is higher by a factor of 2 than the ballooning one due to wider mode structure of the antiballooning mode (Fig. 2(b)) compared to the ballooning one (Fig. 2(a)). The saturated amplitude equals to $\delta B_r/B \approx 10^{-2}$, somewhat larger than the ballooning mode. Similar to the ballooning mode, the damping effects are very small up to $\gamma_d/\omega < 0.1$.

In addition to the α particles drive, we have explored the evolution of TAE $n = 20$ modes driven by the two 16.5MW NBI (1 MeV) beams with different injection geometries: both on axis, both off-axis and one on and the other off-axis. The anisotropic beam particle distributions have been computed with the Monte Carlo NBSOURCE code which includes realistic geometry of the ITER beams [8]. The largest linear growth rates and saturation levels have been obtained for both beams on-axis ($\gamma/\omega = 0.12$ and $\delta B_r/B \approx 10^{-2}$ respectively for the antiballooning mode (Fig.6) without the inclusion of damping effects. The smallest linear growth rates and saturation levels have been obtained for both beams off-axis (γ/ω = 0.09 and $\delta B_r/B \approx 3\text{x}10^{-3}$, respectively).

3. Summary

The structures of the typical and the most driven TAE ballooning and antiballooning eigenmodes with toroidal index n = 20 for the ITER Q = 10 plasma have been computed with the KINX code. The largest growth rates on the linear stage of γ/ω = 0.8 driven by α-particles and nonlinear mode saturation levels of $\delta B/B \approx 10^{-2}$ have been obtained with the VENUS code for the antiballooning eigenmode with ω = 106 kHz. The damping rates as large as γ_d/ω = 0.2 are required to decrease the saturated mode amplitude by a factor of 2. Such a rapid amplitude evolution may violate some of the ordering assumption of our model, i.e. the necessity that $\gamma \ll \omega$. Further convergence studies for high values of n and simulations with other models should be performed for this case.

NBI ions with realistic distribution functions (including anisotropic pitch angle distributions) with the real ITER NBI beam geometry have been computed with the Monte Carlo NBSOURCE code. The largest linear growth rates and saturation level have been obtained for the two NBI on-axis (γ/ω = 0.12 and $\delta B_r/B \approx 10^{-2}$). However, no particle losses have been found from the VENUS orbits simulations for nonlinear saturation levels of $\delta B/B = 10^{-2}$ - 10^{-3} for the mode localized at mid-radius. These results are thus positive for the expected fast particle confinement in the ITER Q=10 scenario, along similar findings with the MEGA and HAGIS codes.

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References

[1] Y. Todo, A. Bierwage, Plasma and Fus. Research, **9**, (2014) 3403068.

[2] M. Schneller, P. Lauber, S. Briguglio, 25th IAEA FEC; S. Petersburg, Russia; 13-18 Oct 2014; TH/P2-6.

[3] M. Yu. Isaev *et al*, 25th IAEA Fusion Energy Conference; S. Petersburg, Russia; 2014; TH/P3-39.

[4] L. Degtyarev *et al*, Comp. Phys. Comm., 103, 10(1997).

[5] W.A. Cooper *et al*, Plasma Phys. Contr. Fus. 53, 024001(2011).

[6] S.D. Pinches *et al*, Phys. of Plasmas, 22, 021807(2015).

[7] A.R. Polevoi *et al*, J. Plasma Fusion Res, 5, 82 (2002).

[8] P.B. Aleynikov *et al*, 36th EPS Conference on Plasma Physics, P4.154, Sofia, (2009).

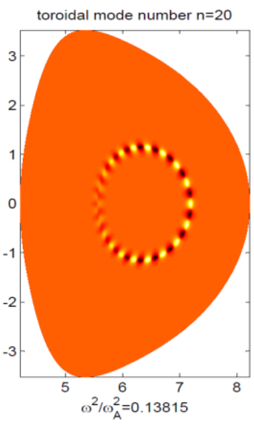

Fig. 1. Plasma cross-section with $n = 20$ TAE mode computed with the KINX code for the ITER Q = 10 plasmas.

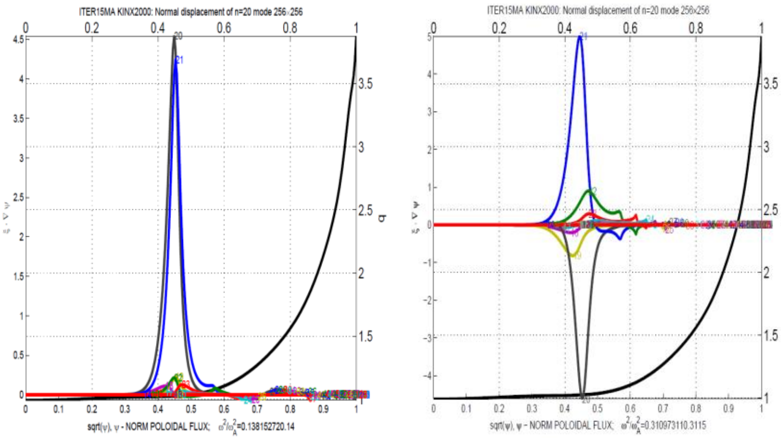

Fig. 2 (a,b). Profiles of the components of the ballooning (a) and antiballooning (b) $n = 20$ TAE mode with poloidal indices $m = 20$ (brown), $m = 21$(blue) and safety factor (black), computed with the KINX code for the ITER Q = 10 plasma.

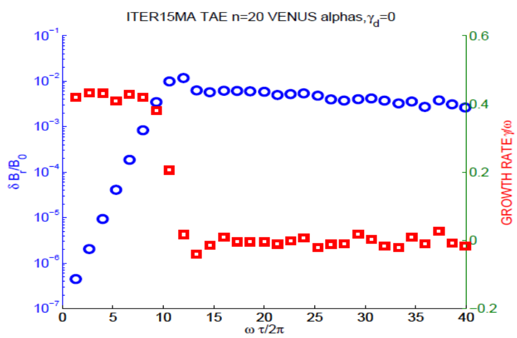

Fig. 3. Nonlinear evolution of the $n = 20$ TAE ballooning mode amplitude (blue circles) and the growth rate (red squares), computed with the VENUS code for the ITER Q = 10 scenario without damping effects.

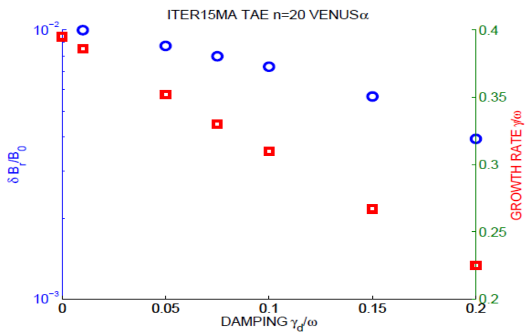

Fig. 4. Maximum amplitude of the ballooning $n = 20$ TAE mode (blue circles) and the total growth rate on the linear stage (red squares) as a function of normalized damping rate γ_d/ω, computed with the VENUS code for the ITER Q = 10 scenario.

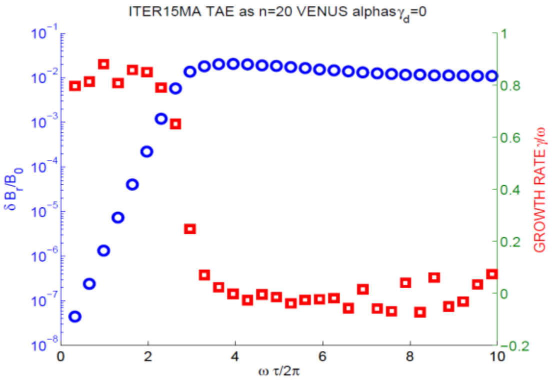

Fig. 5. Evolution of the $n = 20$ TAE antiballooning mode amplitude (blue circles) and of the growth rate (red squares), computed with the VENUS code for the ITER 15MA scenario without damping effects.

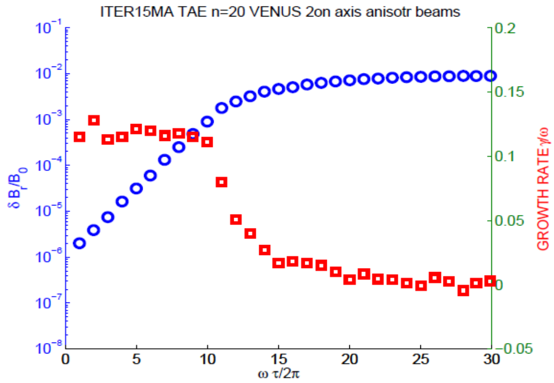

Fig. 6. Evolution of the $n = 20$ TAE antiballooning mode amplitude (blue circles) driven by 2 on-axis NBI ions and of the growth rate (red squares), computed with the VENUS code for the ITER 15MA scenario without damping effects.