Predictive nonlinear studies of TAE-induced $\alpha$-particle transport in the $Q=10$ ITER baseline scenario

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Outline

• Preliminaries
  – HAGIS code assumptions and capabilities
  – Fast particle physics relevant features of ITER baseline scenario, equilibrium and eigenmodes

• Results of HAGIS simulations
  – Linear drive of 129 toroidal Alfven eigenmodes \( n=1-35 \)
  – A discussion of features of TAE nonlinear evolution and comparison to old nonlinear studies
  – Findings for stochastic diffusion of fast alphas
  – Conclusions for redistribution and loss due to alpha driven TAEs in ITER baseline
\[ \dot{\theta} = \frac{1}{D} \left[ \rho_{\parallel} B^2 (1 - \rho_c g' - g\tilde{\alpha}') + g \left\{ \left( \rho_{\parallel}^2 B + \mu \right) B' + \tilde{\Phi}' \right\} \right], \]
\[ \dot{\zeta} = \frac{1}{D} \left[ \rho_{\parallel} B^2 \left( \rho_c I' + q + I\tilde{\alpha}' \right) - I \left\{ \left( \rho_{\parallel}^2 B + \mu \right) B' + \tilde{\Phi}' \right\} \right], \]
\[ \dot{\psi}_p = \frac{1}{D} \left[ \rho_{\parallel} B^2 \left( I \frac{\partial \tilde{\alpha}}{\partial \zeta} - g \frac{\partial \tilde{\alpha}}{\partial \theta} \right) - \left( I \frac{\partial \tilde{\Phi}}{\partial \theta} - I \frac{\partial \tilde{\Phi}}{\partial \zeta} \right) - g \left( \rho_{\parallel}^2 B + \mu \right) \frac{\partial B}{\partial \theta} \right], \]
\[ \dot{\rho}_{\parallel} = \frac{1}{D} \left[ \left( I \frac{\partial \tilde{\alpha}}{\partial \zeta} - g \frac{\partial \tilde{\alpha}}{\partial \theta} \right) \left\{ \left( \rho_{\parallel}^2 B + \mu \right) B' + \tilde{\Phi}' \right\} - \left( q + \rho_c I' + I\tilde{\alpha}' \right) \frac{\partial \tilde{\Phi}}{\partial \zeta} \right] - \frac{\partial \tilde{\alpha}}{\partial t}, \]

Evolving particle phase coordinates

[White & Chance (1984)]

FIXED MHD EIGENMODE STRUCTURE

\[ \delta B = \nabla \wedge (\tilde{\alpha} B_0) \]
\[ \tilde{\alpha}_{km} = \frac{k_m}{\omega_k B_0} \tilde{\phi}_{km}. \]

Evolving wave amplitude and phase

[Berk & Breizman (1995)]
[Candy et al. (1997)]

HAGIS deals with nonlinearities produced when fast particles are resonant and trapped in Alfven modes

Convective transport of holes and clumps


Main parameters of the ITER Q=10 baseline scenario used

- ITER baseline scenario: \( I_P = 15 \) MA, \( B_T = 5.3 \) T, \( R_0 = 621 \) cm, \( a = 200 \) cm, \( P_{\text{NNBI}} = 16.5 \) MW (on-axis) + 16.5 MW (off-axis), \( E_{\text{NNBI}} = 1 \) MeV, \( P_{\text{ECRH}} = 6 \) MW at \( q=3/2 \)
- Plasma consists of D, T, He, and Be
- \( n_D:n_T = 50:50 \),
- \( n_{\text{Be}}(r) = 0.02 \, n_e(r) \).
- Transport code ASTRA was used for plasma parameters and profiles
- \( T_e(0) = 24.7 \) keV, \( T_i(0) = 21.5 \)


Profiles of the safety factor $q(r)$ and magnetic shear in the baseline scenario.

Profile of normalised gradient of alpha-particle pressure and radial positions of values $q_{TAE}=(m-1/2)/n$ (TAE gaps) for different $n$, $m$. 
Some inputs

• TAE modes with toroidal mode numbers $1 \leq n \leq 35$ were computed with the MISHKA code
• 129 modes were found, 3-5 different TAEs for each $n$
• Kinetic damping effects of the modes due to thermal D and T ions, He ash, and electrons were taken from the CASTOR-K analysis\(^1\)
• Analytical estimates for radiative damping of lower frequency TAEs gives $\frac{\gamma_d}{\omega} = 1.3\%$

\(^1\)Rodrigues et al. Nuclear Fusion, 55(8), 083003.
TAE modes

- $n=29$ core-localised TAE, odd parity
- $n=29$ Global TAE
- $n=29$ core-localised TAE, even parity
- $n=16$ Global TAE
Isolated mode linear growth rates from HAGIS

\[ \gamma / \omega \]

- CLTAE even: black
- CLTAE odd: blue
- External or Global mode: red


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Nonlinear saturation of 88 modes $n=15-35$, no damping

Individual mode simulations

- All differences between the two figures are due solely to energy coupling of different modes via common alpha particle population
- Core localised modes are amplified over global modes

Multi-mode simulation
Effects of damping on a single mode

- Rapid modulation of amplitude is characteristic of damping of wave near saturation
- Saturation is reduced by ~50 for $\frac{\gamma_D}{\gamma_L} \approx 0.5$

88 modes n=15-35 coupled with Landau damping

- Saturation achieved in the presence of multiple modes is significantly diminished due to Landau damping, much as for the single mode.
- “Saturation” here means steady amplitude due to balance of free energy in gradient and damping. When this energy is exhausted, the mode will decay.

88 modes $n=15-35$ coupled with Landau damping

- Only CLTAE modes are causing redistribution
- Flattening of profile happens on very long timescales due to low nonlinear bounce frequency and thus slow phase mixing

108 modes n=10-35 with Landau and radiative damping

- Simulations including lower n modes and radiative damping, give basically the same results. We use those amplitudes in simulations below

- Three resonant test particle orbits at 980keV are presented above in the presence of the computed TAE activity

- Widths of stochastic spreading are 7cm for the core orbit, 1cm for the global orbit, and 1mm for the quiet region in between

- A TAE transport barrier near the quiet region is responsible for suppressing avalanche effects (coupling between core and edge localised modes)
Artificially increased amplitude by x50

\[
\frac{\delta B_r}{B_0} \approx 5 \times 10^{-3}
\]

- Mode amplitudes were scaled artificially by a factor of 50 (comparable to the change expected by ignoring Landau damping) and the test particle orbits were followed again.
- Both external and internal regions are stochastic and 50cm wide.
- BUT transport barrier still evident
• Loss of transport barrier and breakdown of confinement
• Quick estimate gives \( \frac{B_p}{B_T} \approx 0.1 \) so perturbations of this size are approaching NTM and disruption levels…
129 modes n=1-35 with damping

- Currently running simulation with all modes found in range n=1-35
- NO damping used for modes n=1-10
- Rogue n=9 mode has resulted
129 modes n=1-35 with damping

- No change in radial redistribution from 108 and 88 mode case, or indeed, when considering CLTAE only
• Quiet region still evident between core and external modes and we conclude that the alpha transport barrier is still present when modes $n=1-35$ are included.
The baseline 15 MA ITER scenario with low shear and q(0)~1 has two distinct regions with very different density of the TAE gaps:

- Core region, \( r/a < 0.5 \), where almost all alphas are, but TAE-gaps are scarce and only highly-localised low-shear TAEs could exist,
- External region, \( r/a > 0.5 \), where alpha-pressure is low, global TAEs exist

For the 129 TAEs found in range \( 1 \leq n \leq 35 \), a transport barrier is found to form at \( \frac{r}{a} \approx 0.5 \) for this q profile which inhibits radial stochastic alpha transport from core to edge global modes when the amplitudes are below \( \frac{\delta B_r}{B_0} \approx 5 \times 10^{-3} \)

The amplitudes attained in HAGIS nonlinear simulation of many modes, when including the effects of Landau and radiative damping, were found to be \( \frac{\delta B_r}{B_0} \approx 1 \times 10^{-4} \), below the threshold for the transport barrier to breakdown by at least a factor of 50, thus radial redistribution was limited to a small region where the core modes were found