Study of Nonlinear Fast Particle Transport in the Presence of Alfvén Waves for the ITER 15MA Scenario

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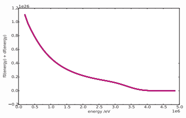
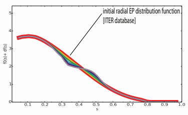
In certain ITER scenarios, a "sea" of small-amplitude perturbations is likely. The crucial question then is, if the interaction between the "sea" of perturbations with the energetic particles (EP) will drive linearly stable or weakly unstable modes such that EP transport occurs in a domino effect.
To investigate this in detail -- for example the EP density threshold for a domino-like transport behaviour, first realistic multi-mode simulations are carried out for the ITER near-stability regime (15 MA scenario) with the hybrid HAGIS-LIGKA [Pinches'98,Lauber'07] model.
To help to understand the nonlinear phase space behaviour, a new test particle diagnostics has been implemented into HAGIS, the HAMILTONIAN MAPPING technique [Briguglio'14].

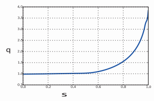
ITER conditions

- alpha particle species
- isotropic in pitch
- slowing down in energy: ΔE=491 keV, Ec=816 keV, E0 = 3.5 MeV
- radial distribution given by TRANSP simulations.





- the q profile assumed in the following is rather flat, close to 1 and monotonically increasing



More details on the ITER 15 MA scenario are to be published [Pinches'14].

Difficulties

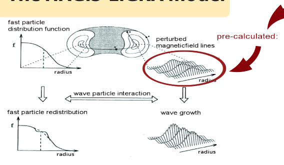
- up to more than 20 modes
- big machine and small modes (high-n)
- many poloidal harmonics

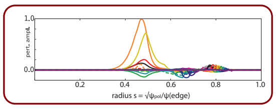
→ high resolution (=up to > 10 Mio. markers)

- small drive

→ long simulation time (ok, as slowing-down time ≈ 0.3 s)

The HAGIS-LIGKA model





[Pinches'98, Lauber'07]

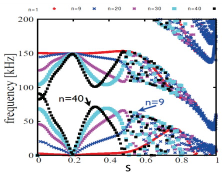
LIGKA is -gyrokinetic, non-perturbative
-linear, global
-eigenvalue solver

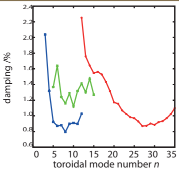
HAGIS is -drift-kinetic, PIC
-hybrid, perturbative,
-nonlinear, electromag.
new: passive species (test particles)

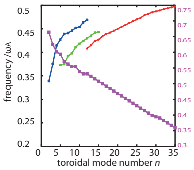
LIGKA results

The Shear-Alfvén Wave Continuum is closed around s ≈ 0.85.

→ TAEs cluster radially dense between s ≈ 0.35 and 0.7





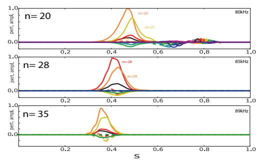


LIGKA finds a broad mode spectrum, the least damped in the main branch around n=28.

With increasing n, the mode radial position slightly decreases, the modes become more localized, the frequency increases.

For intermediate and low-n further TAE branches appear, which are only weakly damped.

More details are published [Lauber'14].

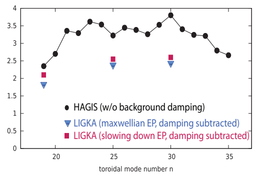


First HAGIS results

Linear HAGIS single mode simulations also reveal the most unstable behaviour between n=21 and n=31.

HAGIS slightly over-estimates the drive, due to the missing of FLR effects, as well as background damping.

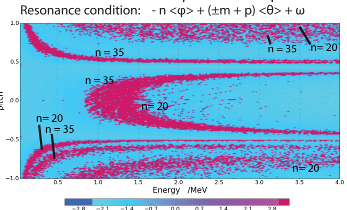
Linear single mode findings:



The resonance lines are broad due to the flat q profile and overlap widely (i.e. are not complementary).

Identification of phase space resonances:

Resonance condition: $-n\langle\dot{\varphi}\rangle + (\pm m + p)\langle\dot{\theta}\rangle + \omega$

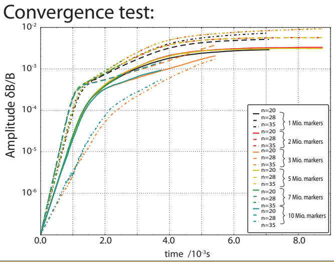


Settings to start with:

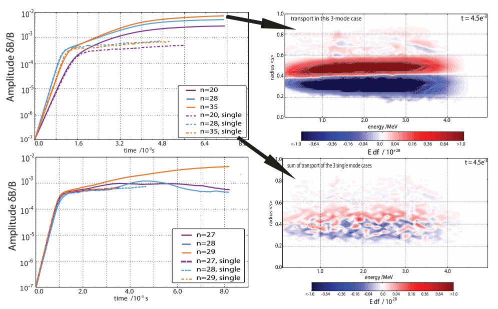
- selected modes only
- no global damping
- no E// damping
- density scan

Convergence tests reveal that the necessary number of markers depends strongly on the scenario, but can exceed 10 million (e.g. for multi mode cases with wide spread radial mode positions).

Convergence test:



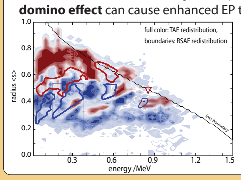
Study with 3 modes: Do earlier findings transfer to ITER ?



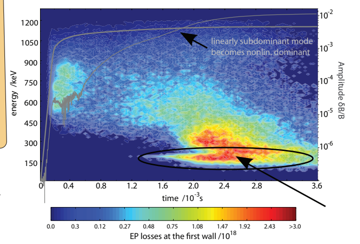
Multi mode behaviour can differ significantly from single mode behaviour: in certain cases, multi mode **saturation amplitude** and **EP transport exceed** by far estimates based on single mode simulations.

However, the behaviour depends strongly on the exact scenario (radial mode distances, resonance pattern). This has also been found in earlier (ASDEX Upgrade related) studies [Schneller'12].

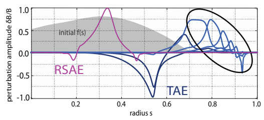
Fixed-amplitude simulations reveal an important multi mode effect (besides higher amplitudes): a **domino effect** can cause enhanced EP transport...

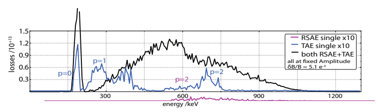


What has been learned from realistic ASDEX Upgrade simulations:



The HAGIS-LIGKA model has been used before to investigate ICRH-heated ASDEX Upgrade discharge #23824. Under realistic conditions, **multi mode** simulations including **all poloidal harmonics** could numerically explain [Schneller'13] the experimentally observed [García-Muñoz'10] EP losses in the **lowest energy range**.



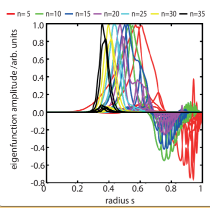


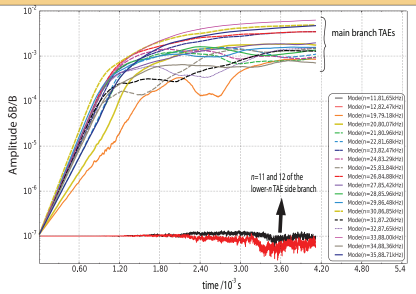
... by a redistribution that is complementary in phase space (if resonances are!). This leads to strongly enhanced EP losses.

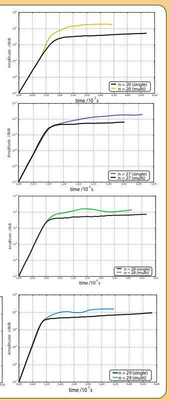
Towards the all-TAEs multi mode case:

Simulation with the n=19 to 35 TAEs of the main branch and two lower-n TAEs. The EP density was set to 50% of the ITER database value; background damping was ignored.

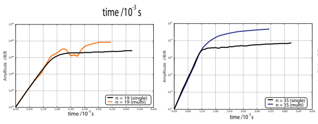
At which density will the low-n TAEs be unstable? How will multiple low-n and intermediate-n TAEs change the picture?







In the investigated multi mode scenarios with more than 7 TAEs all main branch TAEs exceed the single mode saturation level.



Conclusions & Outlook

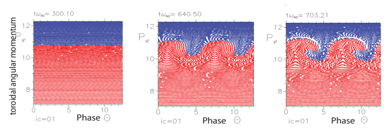
- The linear, gyrokinetic LIGKA model predicts a "sea" of marginally unstable perturbations (up to n=35) for the ITER 15 MA scenario, including weakly-damped lower-n side-branches of TAE, located radially further outside.

- the hybrid, driftkinetic HAGIS code models nonlinearly the interaction of energetic particles with global waves. The wave properties are based on LIGKA calculations. Earlier realistic ASDEX Upgrade studies with the HAGIS-LIGKA model have revealed that multi mode transport (and losses) can significantly exceed quasi-linear estimates based on single mode simulations. These findings were consistent with experimental observation.

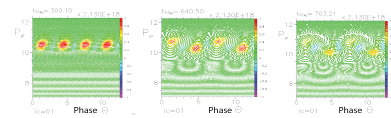
- for the ITER 15 MA scenario, the HAGIS-LIGKA model is used to investigate, whether linearly stable TAEs (e.g. side-branches) can be nonlinearly excited via phase space coupling effects. First simplified multi mode calculations reveal similar, nonlinear multi mode effects as in ASDEX Upgrade simulations. Ongoing work is addressing the conditions under which nonlinear excitation of the lower-n TAE branch can lead to enhanced, domino-like energetic particle transport, exceeding quasi-linear estimates.

Code outlook: Hamiltonian Mapping Technique for HAGIS:

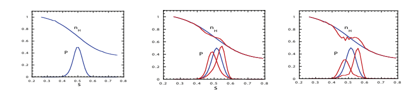
To be able to analyze and benchmark code results not only based on growth rates and saturation amplitudes, a test particle ensemble has been implemented into HAGIS. This allows to use advanced diagnostics [Briguglio'14], by focussing only on the resonant part of phase space (determined by μ and C= E - ω/n Pφ). Especially in the nonlinear phase, this tool will be used to obtain a deeper understanding of saturation mechanisms and nonlinear phase space behaviour. As first example serves here the **ITPA n=6 TAE benchmark** case:



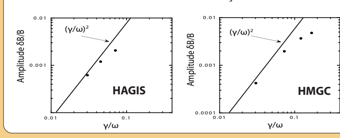
Around the resonant area (color boundary), orbits are perturbed. The red/blue color indicates, that the test particle has an initial toroidal angular momentum (Pφ) below/above resonant value.



The energy exchange bwt. EP and wave (red=driving) splits in the radial space (Pφ).



The amplitude saturates due to flattening and **radial decoupling**: the power transfer (P) decreases.



First results of the nonlinear benchmark between HAGIS-LIGKA and HMGC: both find a scaling weaker than quadratic btw. saturation amplitude and growth rate. This is expected if radial decoupling occurs (not resonance detuning).

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