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Non-linear Energetic Particle Transport in the Presence of Multiple Alfvénic Waves in ITER

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Abstract

This work presents the results of a multi mode ITER study on Toroidal Alfvén Eigenmodes, using the non-linear hybrid HAGIS-LIGKA model. It is found that main conclusions from earlier studies of ASDEX Upgrade discharges can be transferred to the ITER scenario: global, non-linear effects are crucial for the evolution of the multi mode scenario. This work focuses on the ITER 15 MA baseline scenario with $q_0 = 0.986$. The least damped eigenmodes of the system are identified with the gyro-kinetic, non-perturbative LIGKA solver, concerning mode structure, frequency and damping. Taking into account all weakly damped modes that can be identified linearly, non-linear simulations with HAGIS reveal strong multi mode behavior: while in some parameter range, quasi-linear estimates turn out to be reasonable approximations for the non-linearly relaxed energetic particle profile, under certain conditions low-n TAE branches can be excited. As a consequence, not only grow amplitudes of all modes to (up to orders of magnitude) higher values compared to the single mode cases but also, strong redistribution is triggered in the outer radial area between $\sqrt{\hat{\rho}_{\rm pol}} = 0.6$ and 0.85, far above quasi-linear estimates.

1 Introduction

The excitation of global instabilities by super-thermal particles in hot plasmas and the related transport processes are of great interest for the fusion community, due to their importance for burning fusion plasmas. These energetic particles (EPs) are present in magnetic fusion devices due to external plasma heating and eventually due to fusion born α particles. It is necessary that the super-thermal particles are well confined while they transfer their energy to the background plasma. EPs are typically super-Alfvénic and can destabilise Shear-Alfvén, Alfvén-acoustic waves or other global plasma modes by resonant wave-particle interaction (inverse Landau-damping). The resulting non-linear EP transport processes from the core to the edge and the consequential particle losses reduce the plasma heating and the fusion reaction rate. In addition, the EP losses may cause severe damages to the first wall of the device.

Within the last years, significant advances on both experimental and theoretical side have been made leading to a more detailed understanding of EP driven instabilities. On the theoretical side, models have advanced from fluid models for the plasma background to a fully kinetic model for all the plasma species, i.e. background ions and electrons, EPs [1]. This more accurate treatment of the background leads to changes in the linear mode properties such as frequency, damping/growth and mode structure, and can also influence the non-linear dynamics. Since the new physics that is accessible due to a more comprehensive model can directly be validated with experimental data from present-day machines, predictions for several ITER scenarios can be attempted.

In the ITER 15 MA scenario, a "sea" of small-amplitude perturbations is likely [2, 3]. This work presents the first steps towards the prediction of non-linear multi mode EP transport in this ITER scenario with the hybrid HAGIS-LIGKA model. The non-linear HAGIS code [4] treats the EPs drift-kinetically but obtains the non-perturbative mode structures, frequencies and damping from the gyrokinetic eigenvalue solver LIGKA [1]. Recent realistic modeling of double mode scenarios with the HAGIS-LIGKA code [5] not only reproduced experimentally measured EP losses in ASDEX Upgrade [6], but also revealed the importance of linearly subdominant modes as well as mode structure. Hence, the crucial question for the ITER scenario arises, if the interaction between the "sea" of perturbations with the EPs will drive linearly subdominant modes unstable such that EP transport occurs in a *domino effect* caused by the overlap of resonances [5, 7]. In this case, even modes localized outside the region of strong EP drive could be excited non-linearly by EP transport from more core-localized modes. As a consequence, gradient depletion and EP redistribution can exceed the quasi-linear estimates. If so, the preconditions (q profile, background density profile) as well as the consequences (e.g. losses) must be investigated to know if and how these conditions can be avoided.

2 The HAGIS-LIGKA Model

The non-linear multi scale problem of wave-particle interaction cannot be solved in a fully consistent way so far. Although recently, linear as well as first non-linear results for single and multi mode cases were obtained with global codes originally designed for turbulence studies [8, 9], the large computational effort for these approaches limits the possibilities of extended, realistic simulation studies. The joint Culham-IPP code project HAGIS [4] therefore follows a hybrid approach (fig. 1): the EP distribution is evolved in a driftkinetic model and the wave contribution enters the problem via a set of pre-calculated modes. This way, the EP non-linearities are kept, but the MHD-non-linearities are dropped – only the energy transfer between waves and the particles is accounted for. This leads to a redistribution of the EP population in phase space and to the self-consistent evolution of the amplitudes of (multiple) modes and their real frequencies[1]. The wave structures and also their damping is kept fix during a simulation. Saturation is reached in the non-linear stage due to the local flattening of the driving gradient in the radial EP distribution. The stochastization of the EP orbits caused by overlapping resonances with different modes influences the saturation level.

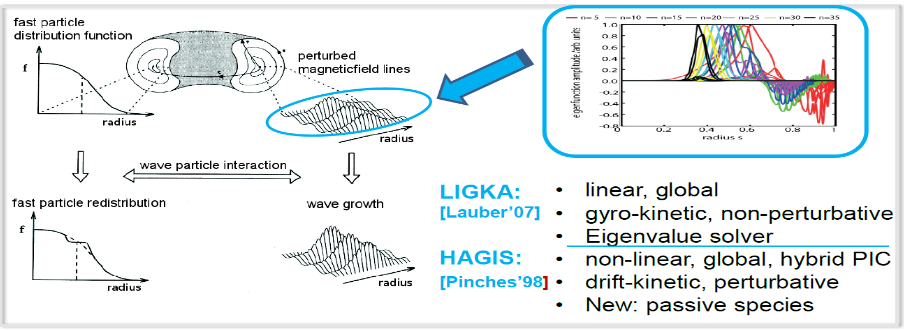

Fig. 1: *Schematic presentation of the* HAGIS-LIGKA *model.*

In ref. [10] it was found that n-n non-linearities, which excite zonal structures, can lead to steeper EP profiles for high amplitude cases. This stabilizing effect is not captured in the present model. Further, it is assumed that the absence of sources and sinks in the model has no relevant effect: due to the separation of timescales (ms -100 ms) the non-linear dynamics is much faster, and even the relevant intermediate time scale of EP redistribution takes place on a time scale well below the one of plasma heating and slowing down.

[1] in this work, if the wave evolution is not fixed, nor prescribed, it will be referred to as "self-consistent" mode evolution.

Mode frequencies, damping and structures that enter HAGIS are pre-calculated by the LIGKA code. The ability to predict the stability of EP driven Alfvén eigenmodes requires a detailed understanding of the dissipative mechanisms that damp these modes. To cover also the important dissipation mechanism of large scale MHD mode coupling to gyroradius scale-length kinetic Alfvén waves, a gyrokinetic description is necessary. With the linear gyrokinetic, electromagnetic and non-perturbative code LIGKA [1] not only growth rate and damping are calculated, but also the global mode structure of the magnetic perturbation in realistic geometry due to the EPs and background kinetic effects.

3 ITER Simulation Conditions

The ITER 15 MA scenario has been analyzed in detail, presented in [3, 11]. The findings which are relevant for this work are shortly summarized in this paragraph: fig. 2 shows the shear-Alfvén-wave continuum for different toroidal mode numbers n and the q profile as shown in fig. 3 ($q_0 = 0.986$). The Toroidal Alfvén Eigenmode (TAE) gaps are closed around[2] $s \approx 0.85$. Due to the flatness of the q profile and the fact that q is very close to 1, the radial TAE positions $q_{\mathrm{TAE}} = (m + 1/2)/n$ decrease monotonously with the mode number n from $s \approx 0.7$ to $s \approx 0.35$ (magenta line in fig. 6) and cluster relatively densely in the radial direction. The resonance overlap leads to additional non-linear effects, which will be investigated in the subsequent chapters. Fig. 5 shows the radial structure of the electrostatic field amplitude for three representative waves as calculated by LIGKA and applied in the HAGIS study of this work.

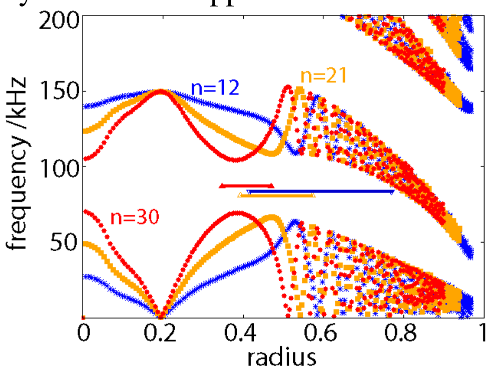

Fig. 2: LIGKA *calculated shear-Alfvén wave continuum (SAW) for the modes* $n = 12, 21, 30$ *in the* ITER *15 MA scenario with the q profile as shown in fig. 3 [3].*

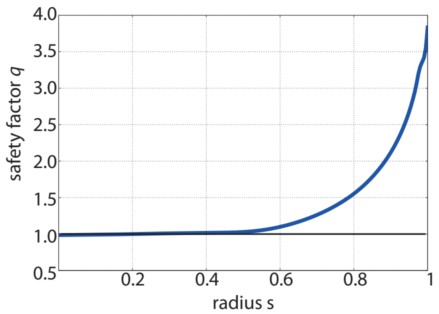

Fig. 3: *q profile used in the* ITER *simulations of this work.* $q_0 = 0.986$.

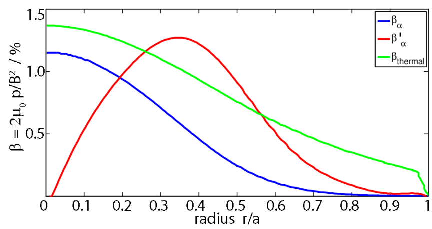

Fig. 4: *Radial profile of EP (fusion-born α particles, blue) and thermal (green) β in the presented* ITER *scenario. Red gives the radial derivative of the EP β. From [2, 11]*

The modeled EP population consists of fusion-born α particles, i.e. distributed isotropic in pitch. fig. 4 shows the EP radial distribution function, which was taken from the ITER database. For the energy distribution, a slowing-down function [12] has been assumed, with $\Delta E = 491$ keV, $E_c = 816$ keV, $E_0 = 3.5$ MeV:

$$f(E) = \frac{1}{E^{3/2} + E_c^{3/2}} \mathrm{erfc}\left(\frac{E - E_0}{\Delta E}\right). \tag{1}$$

In the present work, the EP population generated by neutral beam injection (NBI) is not taken into account yet. For the studied ITER case, the NBI EP lead to TAE drive, roughly in the radial region $s \in [0.4; 0.8]$ [2, 11]. Thus, they act destabilizing and facilitate the scenario described in the following sections.
Due to the high number of modes with many poloidal harmonics, the computational effort for a non-linear study is challenging, even with a relatively low-cost hybrid model. Together with the long time scales which

[2] s is the square root of the normalized poloidal flux.

have to be observed due to generally low drive in the marginally stable regime, this leads to CPU-intensive simulations. In addition, the combination of a large machine size with high toroidal mode numbers n broadens the scales of resolution needed in the simulation. As a PIC code, HAGIS resolution is determined by the number of markers. Convergence tests reveal that the necessary number of markers depends strongly on the scenario, e.g. on the radial distance and n range of the relevant modes and can exceed 10 million for unfavorable constellations, up to 20 million for the 27-modes scenario presented in sec. 5.

4 Linear Stability Analysis of the Alfvén Eigenmodes

A detailed local and global stability analysis has been performed for the ITER 15 MA scenario [3]. In the following, the results for the $q_0 = 0.986$ case which are relevant for the non-linear study presented in sec. 5 are summarized. This specific q profile case was chosen, since it represents a "worst-case" scenario in the sense that it leads to the most unfavorable constellation of gaps for weakly-damped TAE and α particle drive [11]. The LIGKA eigenvalue solver finds relevant eigenmodes up to $n \approx 40$. For intermediate and low n, several weakly damped branches of TAE appear in the gap[3]: $\gamma_\mathrm{d} < 1.0\%$ for the low-n (blue line in fig. 7) and $\gamma_\mathrm{d} < 1.4\%$ for the intermediate-n branch (green line in fig. 7). The main (red line in fig. 7) branch is characterized by the two main poloidal harmonics m of the mode being $m = n, n+1$, whereas for the intermediate-n branch, it is $m = n+1, n+2$ and the low-n branch, it is $m = n+2, n+3$. With increasing n, the TAE modes become more localized, whereas especially the outer, low-n modes have a large number of radially extended poloidal harmonics. This effect is due to the shape of TAE gap towards the edge in the SAW.

Although the TAE position moves inwards, i.e. towards higher ion background temperature with increasing n, the damping decreases (fig. 7). Two effects are responsible for this damping behavior: the frequency increases (fig. 6) due to $\omega_{TAE}/\omega_{A0} = n/(2m+1)$ (which decreases ion Landau damping) and the diamagnetic effects increase for increasing mode numbers. Further, the modes move into the low-shear region, which decreases radiative damping. This effect can compensate for the increase of radiative damping (via $k_\perp \rho_i$) for the more localized mode structures. The least damped modes (of the higher-n main branch) are found around $n = 27$ with $\gamma_\mathrm{d} < 1.0\%$.

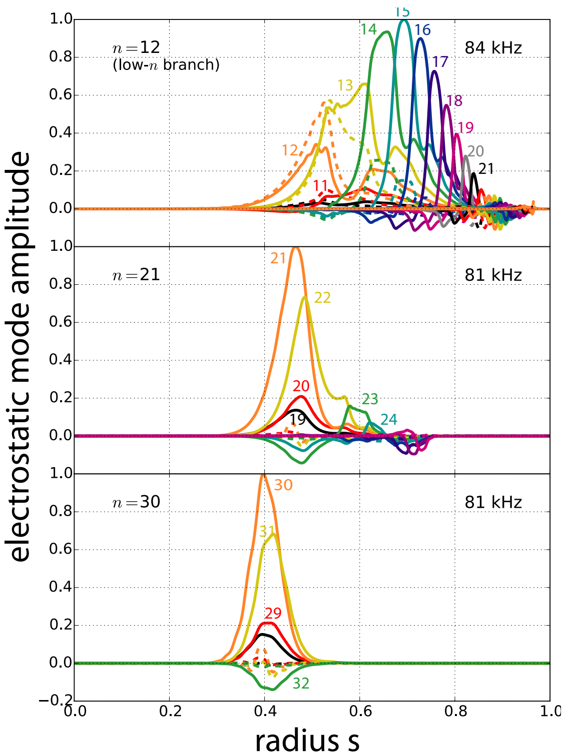

Fig. 5: *Examples of* LIGKA *calculated radial structures of the electrostatic wave potential for the $n = 12$ of the low-n branch, $n = 21$ and $n = 30$ TAE in the* ITER *15 MA scenario with $q_0 = 0.986$. The annotated integers denote the number of poloidal harmonic m.*

Adding the α particle population, a slight destabilization is found linearly ($\gamma < 1.5\%$) for the TAEs between $n = 20$ and 35. This is in agreement with linear HAGIS results, except for the missing finite Larmor radius effects in HAGIS, leading to higher growth rates of about $\lesssim 1\%$. Due to the flat q profile, the resonance lines in phase space are broad, and easily overlap for different modes.

[3] γ_d denotes damping, with "%" indicating the normalization in units 1/s divided by the mode frequency in rad/s. γ represents the linear drive γ_L subtracted by the damping γ_d.

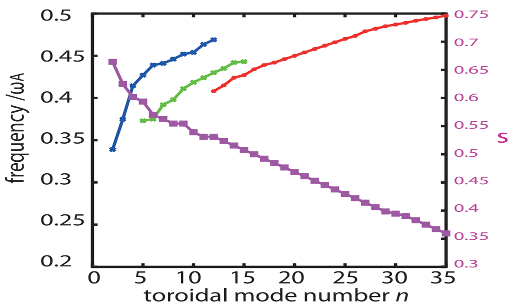

Fig. 6: LIGKA *calculated TAE frequencies (blue,green and red for low-*n*, intermediate-*n *and high-*n *branch) and radial mode position (magenta) for the* ITER *15 MA scenario with* $q_0 = 0.986$ *[3].*

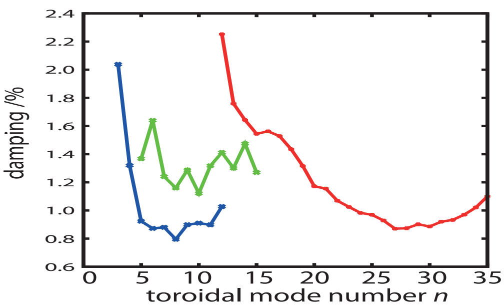

Fig. 7: LIGKA *calculated TAE damping rates (blue,green and red for low-*n*, intermediate-*n *and high-*n *branch) for the* ITER *15MA scenario with* $q_0 = 0.986$ *[3].*

5 Modeling Non-Linear Multi Mode EP Transport

For the understanding of complex non-linear multi mode behavior, realistic ITER conditions are established step-by-step, which also helps to gain confidence about the numerical conditions. To start with, a simplified ITER 15 MA scenario is modeled with HAGIS, e.g. only selected modes are used instead of all TAEs given by LIGKA, and the (small) parallel electric field $E_\parallel$ is still neglected. Convergence was checked for all numerical parameters at every level of the investigation. In the following, only the most realistic compromise between computational effort and relevant physical features will be discussed. The respective scenario was set up with the least damped 27 TAE modes that were found in the linear analysis in the main branch (red in fig. 7), $n = 12..30$ and in the low-n branch (blue in fig. 7), $n = 5..12$. Since the importance of poloidal harmonics is known from earlier ASDEX Upgrade studies [5], all harmonics with a peak greater than 25% of the mode's maximum peak were taken into account. This affects mostly the low-n branch being simulated with up to 12 poloidal harmonics, whereas the high-n branch is characterized sufficiently by 2 harmonics only. The major motivation to focus on the main and the low-n branch is not only the low damping: together with the effect of multi mode coupling, this can lead – as will be shown later – to a non-linear enhancement of the low-n branch, despite its radial location outside the maximum α particle drive at $s = 0.4$. As a consequence, modes with rather high amplitudes can possibly cover a large radial range, and subsequently, EP redistribution, especially in the outer core region can exceed quasi-linear estimates.
In order to test the validity of quasi-linear models (which require a reduced computational effort) this section is dedicated to work out a comparison between a quasi-linear (e.g. [13, 14]) and a non-linear approach. In a quasi-linear model, one can estimate the mode growth rates γ from linear single mode simulations, since $\gamma \propto \beta_{\mathrm{EP}}$ (see e.g. the[4] β scaling of high-n single mode linear growth rates in fig. 10). Mode saturation amplitudes A can be estimated from quadratical scaling $A \propto (\gamma/\omega)^2$ w.r.t. the single mode linear growth rates over the mode frequency ω. For the ITER 15 MA baseline scenario $q = 0.986$, the amplitudes in single mode simulations follow quite well such quadratic scaling with the mode linear growth rate, as shown in fig. 8. In general, a critical plasma β_{crit} can be determined, at which the linear growth rate γ_{L} equals the damping γ_{d}, and the mode will be marginally stable $\gamma \approx 0$. In quasi-linear theory it is assumed that overlap of resonances causes diffusive EP transport as soon as the linear instability threshold is exceeded, i.e. $\beta \geq \beta_{\mathrm{crit}}$. Subsequently, the diffusive transport relaxes the EP distribution function such that the local β takes values around β_{crit}. Fig. 11 shows the final EP density gradient depletion caused by all 27 relevant modes together, simulated with amplitudes fixed at their single mode simulation level (in the following, this model will be referred to as

[4]in the following, β denotes the EP plasma beta, i.e. ratio of EP pressure over mag. background field.

"quasi-linear" HAGIS simulation). The derivative of it is comparable but slightly above the local gradient of $\beta_{\rm crit}$ at each mode location (red dots). Thus, $\beta_{\rm crit}$ provides a lower estimate for profile relaxation here.

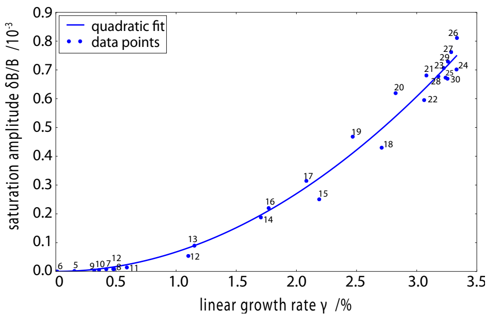

Fig. 8: *Saturation amplitude depending on growth rate for single mode simulations at the default radial EP density profile. The annotated labels give the toroidal mode number n.*

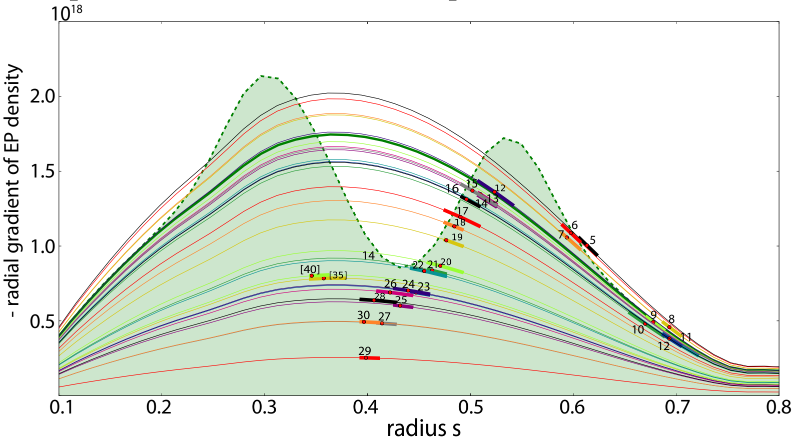

Fig. 9: *"Quasi-linear" radial EP density gradient depletion: multi mode simulation with amplitudes fixed to single mode saturation levels. The thick solid green line shows the initial, the dashed green line (with shadowed area beneath) the final value of radial density gradient. The red dots indicate the local critical density gradient of each mode, at the mode peak position with the solid lines giving the default EP density gradient scaled to that critical value. The thicker area of the lines visualizes the radial peaks of the mode structure.*

In the following, it will be investigated, whether this quasi-linear estimate is a valid assumption by modeling the mode evolution of all relevant 27 modes self-consistently. Scaling the default radial EP density profile to 30% results in marginally stable modes, as quasi-linearly predicted (e.g. from fig. 10). Scaling the EP density profile to 50% of the default reveals mode growth for the modes in the high-n branch, whereas the modes of the low-n modes are damped. This non-linear multi mode evolution is roughly consistent with the quasi-linear expectation, as shown in fig. 11.

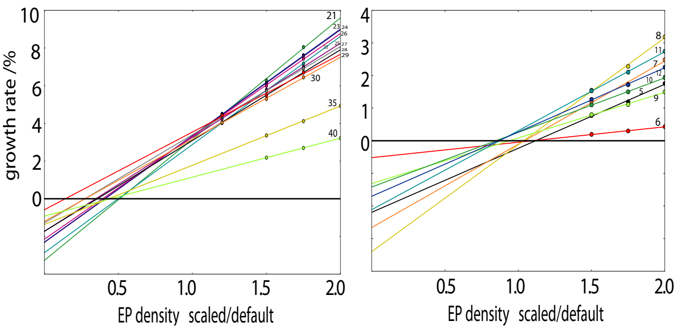

Fig. 10: *Scaling of linear growth rate $\gamma_{\rm L}$ subtracted by the* LIGKA *damping $\gamma_{\rm d}$ (circles) over EP density in the single mode cases for high-n modes (right) and the low-n branch (left). Each solid line represents the linear fit for the higher (β, γ) values of the respective mode n (annotated number), represented by the circles of the respective color.*

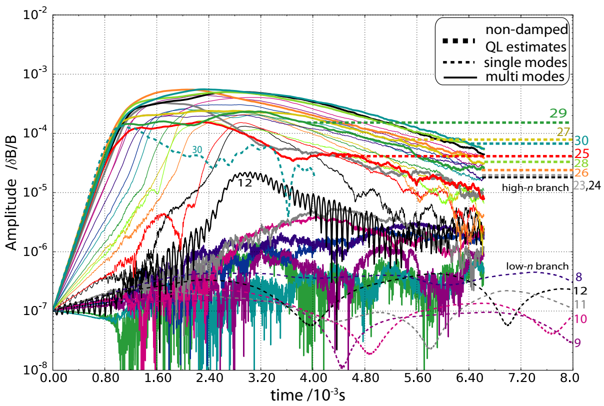

Fig. 11: *Non-linear multi mode evolution in the case of EP density scaled to 50%: (solid lines, for all 27 modes), single mode evolution (dashed lines, for selected modes of the low-n branch and the $n = 30$ mode of the high-n branch) and quasi-linear estimate (dotted lines, only the 8 highest n modes are non-damped). Each color refers to a particular mode.*

If the radial EP density profile is scaled up to its default value as predicted for this ITER scenario, the self-consistent wave evolution in the multi mode scenario differs significantly from the single mode simulation, i.e. from the quasi-linear expectation: at around $3ms$, the waves of the low-n branch (blue in fig. 12) get strongly excited and their amplitude grows to values of roughly more than one order of magnitude (a factor of 5 to 65) higher than in the single mode saturation (light blue in fig. 12). While non-linearly, some of the low-n modes (especially $n = 12, 11$) become one of the dominant modes, the ratio of linear growths γ/ω in the multi mode over the single mode cases is similar (1 ± 0.1) for the modes $n > 12$ (for the $n \geq 12$ modes it is comparable (1 ± 0.6) in the early linear phase). This emphasizes the strong non-linear effect of the multi mode behaviour, that cannot be foreseen linearly. The amplitudes of the high-n branch modes (red in fig. 12) in the multi mode case reach values that are enhanced slightly, by a a factor of 5 at most for $n > 12$. For both, low- and high-n branch the non-linear multi mode dynamics is non-trivial – modes reach high amplitude regimes at very different times t. While the low-n branch grows in 3 phases ($t < 0.4$ ms: like single mode, 0.4 ms $< t < 3.2$ ms: first enhancement until a slight "saturation", $t > 3.5$ ms: second enhancement). The behavior of the high-n branch starts to differ from single mode evolution only at the onset of its saturation ($t \approx 0.6$). This saturation is higher than in the single mode case and followed by a second enhancement of high-n modes at around $t \approx 4.5$ ms, when the low-n modes have reached relevant amplitudes of $\delta B/B \approx 10^{-3}$.

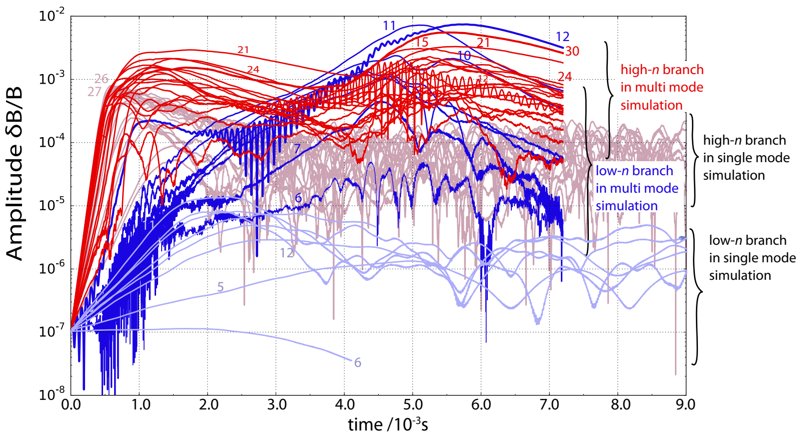

Fig. 12: *Default radial EP density profile case: self-consistent multi mode evolution (strong colored solid lines) compared to the single mode evolution for all 27 modes (light colored solid lines). Blue represents modes of the low-n branch, red of the high-n branch. The integers denote toroidal mode numbers n.*

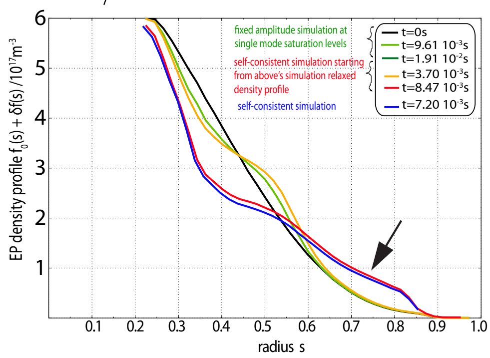

Fig. 13: *Radial EP redistribution for the self-consistent multi mode simulation (orange line for an earlier time point, red line for the final time point) starting from the quasi-linearly relaxed EP density profile (converged over time to the dark green line). The blue line the final EP distribution in the self-consistent multi mode simulation starting from the default initial EP density profile (black line).*

To understand the non-linear multi mode behaviour, it is helpful to look at the temporal evolution of EP redistribution: until $t \approx 4$ ms, the radial redistribution does not exceed the relaxed profile observed in the fixed amplitude multi mode simulation (green lines in fig. 13). However, this redistribution not only leads to a steeper EP density gradient at the radial position of the low-n modes, but also provides more EP in the radial region of these modes. There is a critical redistribution that triggers the excitation of the low-n modes, which can be reached only due to the large amount of more core-localized modes in the high-n branch: a reduced scenario simulation of only the highest amplitudes and radially most extended modes ($n = 8, 11, 12, 12, 18, 21, 24, 30$) did not lead to sufficient redistribution to excite the low-n modes, although the high-n modes reached similar saturation amplitude levels compared to the full scenario simulation. With the low-n modes reaching levels around $\delta B/B \approx 10^{-3}$, massive EP gradient depletion sets in, and EP are redistributed radially outwards to $s \approx 0.8$ (see blue line in fig. 13). A similar depletion occurs even if the already quasi-linearly relaxed EP density profile was chosen as initial condition (see red line in fig. 13).

It is interesting to note, that the radial redistribution is energy dependent (see fig. 14). This is due to the low-n modes being radially quite broad, such that they resonate better with EP of higher energies with large bounce orbit widths. Since these modes are located around $s > 0.5$, the EP density depletion moves radially towards the outer core region with increasing energy.

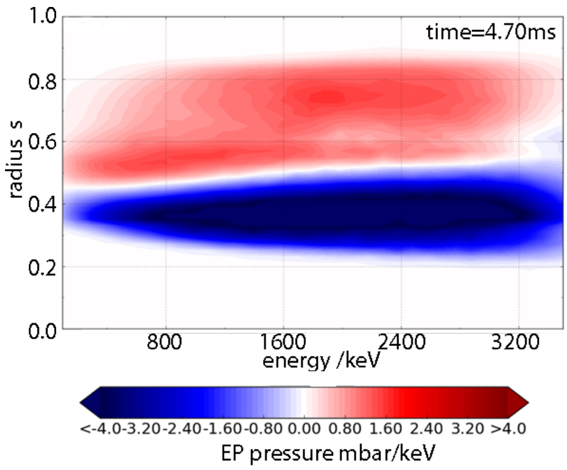

Fig. 14: *Change of EP pressure in energy radial space (red: growing, blue: reduced w.r.t. initial state) for the full 27 modes scenario at default EP density profile, at* $t = 4.7$ ms.

In the evolution of the density depletion, big differences can be observed between the self-consistent non-linear multi mode scenario (with 27 modes) and the quasi-linear HAGIS simulation with the same modes (amplitudes fixed at the respective single mode saturation level): while the quasi-linear case converges in time towards a depletion slightly above the local values of β_{crit} (fig. 9), the non-linear scenario also reaches this state (fig. 15, left), but with the low-n modes exceeding amplitude levels of $10^{-3}\delta B/B$, broad redistribution sets in. The density gradient in the outer core region is depleted rapidly (fig. 15, right), triggered by the radial overlap of the growing low-n modes with the higher-n modes (this is visualized by the thick lines in fig. 15, left). This domino behaviour is clearly a non-local effect, which is avoided in the quasi-linear scenario by a transport barrier between the outer, low-n and the inner, high-n branch: the locally very high EP density gradient (fig. 15, left) around $s \approx 0.55$ cannot be depleted because there is no radial mode overlap at amplitudes above certain threshold (around $\delta B/B \approx 10^{-3}$). The situation changes rapidly, as soon as broad, low-n modes grow, triggered by gradient steepening due to EP refill from the inner, high-n modes.

6 Conclusions and Discussion

This work presented a non-linear investigation on the interaction of energetic particles with multiple global modes in the ITER 15 MA scenario using the hybrid HAGIS-LIGKA code package. The addressed question is, if the overall energetic particle transport remains within the quasi-linear estimates or if possible non-linear excitation of linearly stable TAEs via phase space coupling effects leads to enhanced, domino-like energetic particle transport. The challenge for an investigation arises not only from the high amount of modes and poloidal harmonics, but also from the high resolution range needed due to the large machine size combined with high toroidal mode numbers n. For the ITER 15 MA scenario with $q_0 = 0.986$ the linear, gyrokinetic, non-perturbative code LIGKA predicts a radially dense cluster of TAEs up to toroidal mode number $n \approx 40$ that can be categorized into three different branches: low-n, intermediate-n and high-n. As discussed in ref. [3] a flat q with q_0 close to 1 causes a dense cluster of modes that facilitates the excitation of edge TAEs. Therefore, the $q_0 = 0.986$ scenario investigated in this work is a "worst-case", compared to other scenarios with different q shaping (as provided in ref. [11]).

Non-linear HAGIS simulations were carried out, taking into account the least damped modes of the core-localized high-n branch ($n = 12..30$) and the weakly damped low-n branch ($n = 5..12$) with modes in the

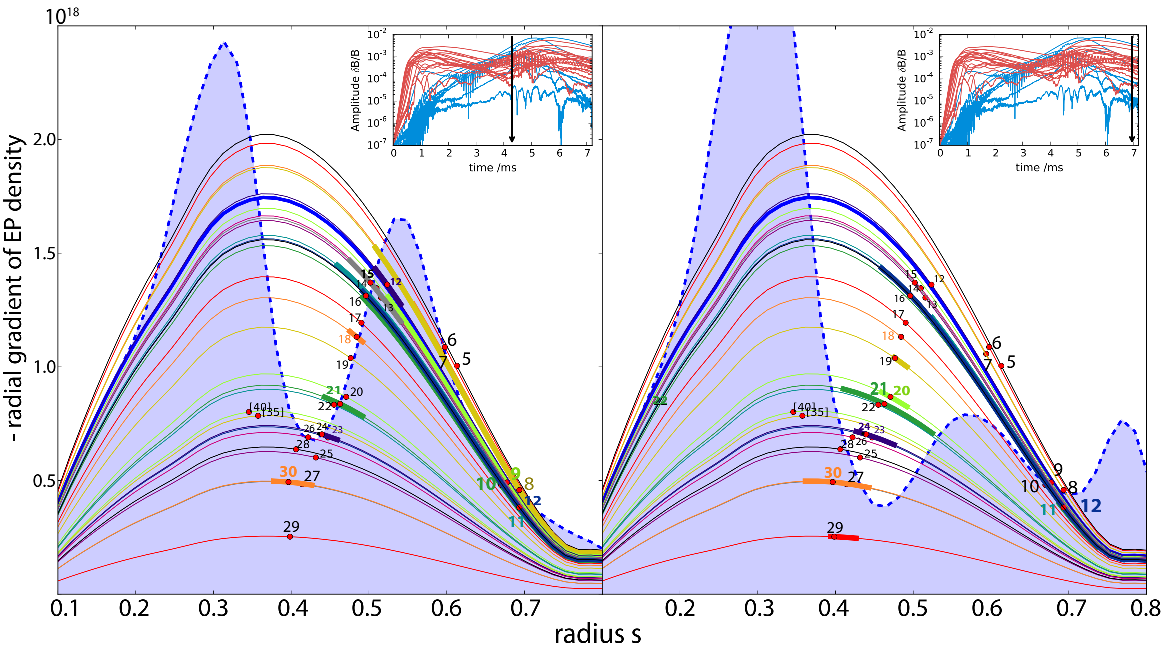

Fig. 15: *Non-linear radial EP density gradient depletion in the self-consistent multi mode simulation (27 most relevant modes) with default initial EP density profile (thick blue line) for two different times during the simulation (left: $t = 4.3$ ms, right: $t = 6.9$ ms, see arrow in the respective insert for mode amplitude constellation at that time). The thick solid blue line shows the initial, the dashed blue line (with shadowed area beneath) the value of radial density gradient at time t. The red dots indicate the local critical density gradient of each mode, at the mode peak position with the solid lines giving the default EP density gradient scaled to that critical value. The thicker area of the lines visualizes the radial region, where the amplitude of the respective mode exceeds $10^{-3}\delta B/B$ at the respective time.*

outer core region. It was shown, that mode amplitudes and EP redistribution stay well within quasi-linear expectations, if a certain EP density threshold is not overcome: the relaxed radial density gradient remains well above the critical gradient. In the scenario with full, default EP density profile, it was found, that the phase space redistribution caused by the (sufficiently large) number of inner, high-n modes triggers the excitation of the otherwise marginally unstable outer modes of the low-n branch (enhancement of a factor between 5 and 60). This excitation is very sensitive to sufficient redistribution by the high-n modes. It leads to the rapid depletion of the radial EP density gradient in the region of $s \approx 0.55$. This non-local effect is based on the radial overlap of the two branches that forms, at the time when the radially broad low-n modes grow towards $\delta B/B \approx 10^{-3}$. Therefore, no such depletion occurs in the quasi-linear scenario, with mode amplitudes fixed to the much lower single mode saturation levels, which effectively also restrict the modes locally and therefore create a transport barrier. The same transport barrier is present for more favorable q profiles which leads to a different Shear-Alfvén gap structure with increased continuum damping, either via a steeper q-profile or a very flat background density profile.The resulting more localized modes would prevent radial resonance overlap and lead to radially well separated redistribution. The domino-like depletion in the non-linear simulation shows, that for certain “worst-case” scenarios, it might not be sufficient, to investigate EP redistribution on a quasi-linear basis only, without taking into account non-local and multi mode effects. Even if (on the transport time scale), the background density and current (thus, q) profiles are leading to a stable situation, small changes (towards more box-like shape) in either background density or current can lead to“overshooting” domino-like EP redistribution and TAE drive. The final situation might even oscillate around the marginal stable profile.

7 Outlook

The presented work raises the question, if a large amount of EP losses could be expected for this (or other) ITER scenarios. Since the redistribution in the worst-case reaches out to $s \approx 0.8$, possible interaction with the 3D field ripple perturbation has to be taken into account. A collaboration with the ASCOT code [15] simulating the edge-localized field ripple with given LIGKA perturbations is already ongoing. It allows for a first, preliminary estimate, that the amount of EP losses would not be dangerously large, since the loss regions calculated by ASCOT and the radial extension of high amplitude areas in the HAGIS simulation barely overlap. However also other AEs (here only TAEs) and global MHD modes such as islands, have to be included.
Beside the question of real losses, it is planned in the near future to investigate the physical mechanisms and relevant time scales of particle redistribution. Especially it will be studied whether EP are moving from the center to the edge on the basis of resonant or diffusive processes in the different stages of multi mode-particle interaction. For that study, the newly implemented HAMILTONIAN MAPPING TECHNIQUE [16] will be used within HAGIS in combination with prescribed amplitude evolution to lower the CPU costs of the simulation.

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