Quasi-linear relaxation of energetic ions in ITER mediated by Alfvén instabilities[1]

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Due to their high energies at birth, $3.52MeV$ fusion alpha particles will be superalfvénic with the ratio of their birth velocity to the characteristic Alfvén speed evaluated as $v_{\alpha 0}/v_A = 1.86$ in planned ITER experiments whereas for $1MeV$ neutral beam injection (NBI) D fast ions that ratio will reach $v_{b0}/v_A = 1.43$ [1]. It is expected that the confinement of those energetic particles (EPs) could be endangered by the excitation of low-frequency Alfvénic eigenmodes (AE) such as toroidicity-induced Alfvén eigenmodes (TAE) and reversed shear Alfvén eigenmodes (RSAE). Background plasma parametric dependencies of various damping and driving rates has been investigated for adequate EP confinement in future fusion devices (see [1]). Both are well represented and verified in NOVA-C framework [2].

An application of the linear stability theory together with a new formulation of quasilinear (QL) theory [3] for discrete modes allows to evaluate the EP distribution relaxation in burning plasma (BP) conditions with additional contributions from the background microturbulence-driven effective pitch angle scattering [4]. Two important damping mechanisms that shape the EP profiles and control EP losses to the wall were identified [1]. They are the thermal ion Landau damping which is dominant near the plasma center, and the thermal trapped electron collisional damping that dominates near the plasma edge [5]. QL simulations performed with the help of a new, resonance broadened QL code (RBQ) takes those mechanisms into account in a perturbative manner [4]. What follows from previous studies, however, is that the EP relaxation is quite sensitive to the microturbulence level. This particular topic is out of the scope of our work. Nevertheless it is important to state that without that knowledge, RBQ can provide a rather optimistic level of EP relaxation.

1. TAE/RSAE LINEAR STABILITY IN ITER STEADY-STATE SCENARIO

A comprehensive stability analysis was performed with the help of the ideal MHD code NOVA [6] and its hybrid drift kinetic extension NOVA-C [2]. This was done for the Alfvénic eigenmodes in the frequency range spanning from the geodesic acoustic mode frequency up to the Ellipticity-induced Alfvénic Eigenmode (EAE) gap. In Fig.1 we present the ITER steady-state plasma profiles as computed by the ASTRA code [7]. One feature relevant to AE stability is that the steady-state ITER scenario presented here, unlike earlier baseline case scenario [1], is characterized by fusion α-particle pressure profile twice and beam ion beta profile ten times larger. It is not surprising that the NBI contribution to AE instability was ignored in follow-up studies [8, 9].

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Fusion α's and beam ions with distinctly different distribution functions (DF) are included in simulations. Their DF's contour maps are illustrated in Fig. 2. Both distribution functions are shown near their injection (birth) energies in the canonical angular momentum, P_φ, and the adiabatic moment, $\lambda = \mu B_0/\mathscr{E}$ plane. Given the ratio of their super-Alfvénic velocities to the Alfvén speed it is expected that the AE instability drive will be maximized against $v_{\alpha,b0}/v_A$ ratio. Furthermore, one can see jumps at the separatrix between the passing and trapped ions of alphas on the right figure. Those jumps are physical and they are due to the jumps in the drift orbit precession times associated with the transitions from trapped to passing ion orbits and vise versa.

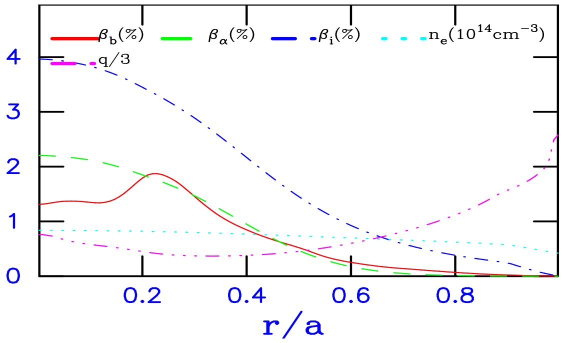

FIG. 1. *Plasma profiles of ITER steady-state scenario used in simulations. Shown are the radial profiles of beam beta, β_b, fusion product alpha particle beta, β_α, thermal ion beta β_i, electron density, n_e, and safety scaled by factor as $q/3$.*

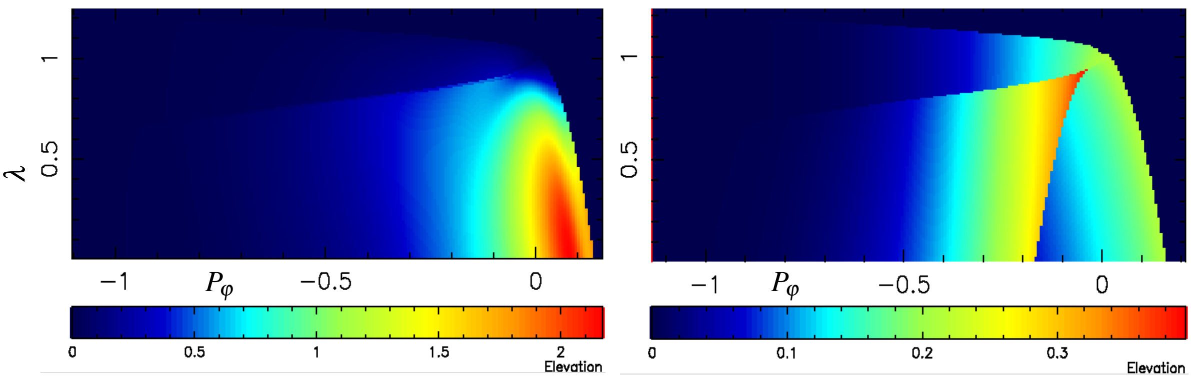

FIG. 2. *Beam ion (left) and alpha particle (right) distribution functions shown as contours in the plain P_φ, λ. Both DF are the sums over the distribution of different signs of EP parallel component of particle velocities, $\pm|v_{\parallel}|$.*

NOVA has found around 600 AE modes of interest out of which NOVA-C identified around 40 unstable of marginally stable eigenmodes for subsequent RBQ runs. The AE stability is addressed by the kinetic NOVA-C code which incorporates rich physics including the background dampings and advanced fast particle representation that allowed favourable benchmarks against main available codes [10]. We show AE growth rates in Fig. 3. More detailed report will be presented at the IAEA FEC this year.

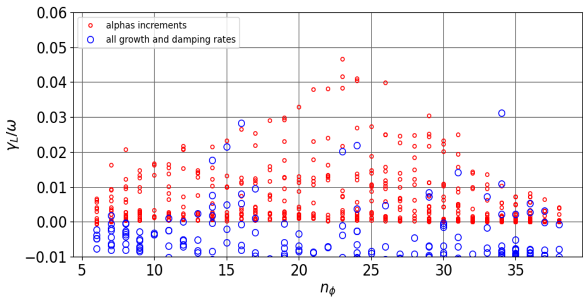

FIG. 3. *Sum of AE growth and damping rates for each mode are computed for the unstable and marginally stable eigenmodes. They are shown as blue open circles. Net growth rates due to fusion α-particles only are shown as smaller red circles. AE net growth rates include beam ion drive.*

From the linear AE stability results several important observations follow. First, our linear AE stability analysis is consistent with earlier results

[8, 9] especially the toroidal mode number range of the unstable AEs and their characteristic growth rates. The growth rates have the maximum or rolloever point at around $n = 20 \div 30$ in those calculations. Second, two regions in radius have strongest contributions to the growth rates: near the center and near the q_{min} location. Third, the multiplicity of AEs will likely result in the overlapping of the resonances in the constant-of-motion (COM) space due to the nonlinear broadening. Fourth, the dominant damping rate that controls the EP profiles near the edge is the trapped electron collisional damping. For reliable predictions such damping is required in simulations. Ignoring it would change the radial domain of EP confinement and, as a result, will overestimate the loss fraction such as reported in Ref.[11].

2. QUASI-LINEAR MODELING OF FAST PARTICLE RELAXATION

The recently built numerically efficient, self-consistent QL code RBQ is applied to ITER steady-state scenario [7]. It is capable of addressing the EP confinement in the presence of several to multiple Alfvénic modes by following the time evolution of their amplitudes and by advancing the EP distribution function in the COM space. This can be done either within the RBQ code itself or by providing the diffusion and convective coefficients for a subsequent calculation by a Whole Device Modeling (WDM) package such as NUBEAM [4]. Furthermore, the RBQ code is already interfaced with the WDM TRANSP code and has preliminary shown a good agreement in its application to DIII-D critical gradient experiments [4].

We applied RBQ to ITER steady state plasma characterized by 40 marginally unstable/marginally stable AEs and prepared the COM diffusion coefficients for WDM processing. Both beam ion and alpha particle plasma components contribute to the AE drive although linear stability indicates that beam ions have on average the growth rate twice as high. This is because beam ions are injected into the most unstable location in the COM space.

RBQ pre-computed diffusion coefficients are quite high locally where most of the unstable modes are driven unstable near the point of q_{min}, reaching values up to $\lesssim 10^2 m^2/sec$ at the q_{min} location and going down to $\sim 1 m^2/sec$ toward the periphery. This implies that local flattening of EP profiles near q_{min} is expected but overall the EP redistribution can be quite modest.

As we show in Fig.4, the AE amplitudes can reach values $10^{-4} \div 10^{-3}$ for AEs whereas no significant fast ions losses to the wall were seen. In the final stage, the standalone NUBEAM package was applied to evolve the fast ion distribution functions more accurately in the COM space. Both RBQ internal calculations and NUBEAM standalone calculations have found that the EP confinement with the Coulomb scattering does not result in significant fast ion losses, which is consistent with earlier studies [8, 9].

Microturbulence, however, can significantly boost the AE amplitude saturation by broadening the phase-space locations near the WPI resonances [4, 12]. For example, it was found that AE amplitude goes up significantly with the anomalous scattering, $\delta B_\theta/B \sim \nu_{eff}^2$ and EP losses can be enhances as a result.

Such strong dependence of fast ion relaxation on the microturbulence intensity, however, does not allow us to reliably predict the fast ion confinement in ITER advanced steady state scenarios without quantitative predictions of the microturbulence levels.

In summary, we have found that the beam ions injected at $1MeV$ lead to stronger growth rates to excite AEs in comparison with fusion alpha particles, which are born with the source isotropic in pitch angles, $\chi = v_{\parallel}/v$. This was not the case in earlier studies [1]. On the other hand, the background microturbulence can enhance EP losses in ITER plasmas which deserves future careful attention. Present applications of RBQ and NUBEAM to ITER steady state case has shown a weak loss of fast ions to the wall at the level of 2%.

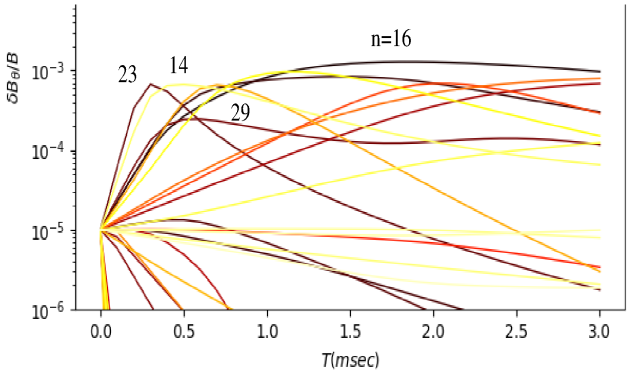

FIG. 4. *Time evolution of unstable and marginally unstable AEs computed by the RBQ code over* 3 *msec time window. Toroidal mode numbers of the most unstable modes are shown on the figure.*

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