IMPACT OF LONG-TERM SIMULATIONS ON FAST ION RELAXATION IN STEADY-STATE ITER SCENARIOS

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We present a novel effect: the long-term evolution of fast ion density profiles, resulting in a hollow shape profiles at the plasma center in ITER steady-state scenarios. This process unfolds over long timescales, exceeding the fast particle slowing-down time. In the cases studied, fast ion relaxation is driven by both classical confinement mechanisms as well as by unstable and marginally unstable Alfvén Eigenmodes (AEs).

The fast ion confinement is the challenge for burning plasmas where high-energy fusion products or fast ions from auxiliary heating can remain confined long enough to offset thermal plasma energy losses. To address it, we investigate one of the most detrimental collective phenomena: the instability of low-frequency, sub-cyclotron AEs, such as toroidicity-induced Alfvén Eigenmodes (TAEs) and reversed shear Alfvén Eigenmodes (RSAEs) [1], within the anticipated ITER steady-state scenario [2].

Using a novel, quasi-linear approach we model the relaxation dynamics of energetic particles (EPs) in the presence of AEs. We find that these modes influence both neutral beam ions and alpha particles. However, under the assumptions of classical particle slowing-down, the resulting fast-ion transport remains modest [3]. Although included in simulations the impact of the microturbulence does not strongly effect those results. Our analysis confirms the formation of a hollow EP profile in the plasma center of the ITER steady-state scenario. This phenomenon arises from a combination of several factors, all of which act on long timescales. The primary effect is attributed to anomalous local EP diffusion near the plasma center, which is significantly enhanced by neoclassical effects. These effects are closely related to the radial orbit width of EP drift orbits and contribute to the observed profile evolution.

We make use of a comprehensive stability analysis of the low-frequency Alfvénic spectrum, utilizing several reduced models to introduce a novel approach which accounts for a time-evolving energetic particle (EP) source. Found results are illustrated in the enclosed figure.

Our approach incorporates the temporal evolution of EP beta, $\beta_f(t)$, provided by TRANSP simulations. Applied analysis includes the Alfvén Eigenmode-driven EP diffusion coefficients obtained by recently developed resonance-broadened quasi-linear (RBQ) model [4] applied at a single time t_0:

$$D_{xvf}(\Gamma : t) = D_{xvf0}(\Gamma : t_0)(\beta_f / \beta_{f0})^{4/3},$$

where the dependence on EP pressure is derived theoretically [6], and is based on the linear relationship between the AE growth rate and EP pressure, $\gamma_{LAE} \sim \beta_f$, where *LAE* stands for linear AE growth rate. The RBQ simulations accurately account for the dominant wave-particle nonlinearities, which are consistent with the quasi-linear approach [5].

Our simulations include the ideal MHD AE mode structures computed by the ideal code NOVA and evaluate their growth and damping rates with the help of its kinetic extension NOVA-C [7], which operates in the constant of motion (COM) space. The AE linear stability involves rich physics incorporated in NOVA-C model. It includes the fast particle finite orbit and Larmor radius effects, thermal ion and electron Landau damping and drive, trapped electron collisional and radiative damping. RBQ simulations were validated against DIII-D critical gradient experiments and verified against analytic theory and kick model [4,7].

It is worthwhile to note that beam ions drive AE instabilities with stronger growth rates than alphas due to beam distribution function being strongly anisotropic in pitch angles since they are delivered into the most contributing to AE instability velocity space region [3]. The subsequent QL simulations are supported by NOVA-C modeling using the wave-particle interaction (WPI) matrices of the AEs of interest[4].

The quasi-linear code RBQ then computes AE amplitude and the resulting COM diffusion coefficients of both fast ion species. We have previously found that an important element of fast ion relaxation in the presence of AEs is the pitch angle scattering due to the background microturbulence [9]. This effect is novel and is often overlooked in initial value simulations. It leads to EP velocity pitch angle scattering and needs to be included in predictions of future burning plasma operations.

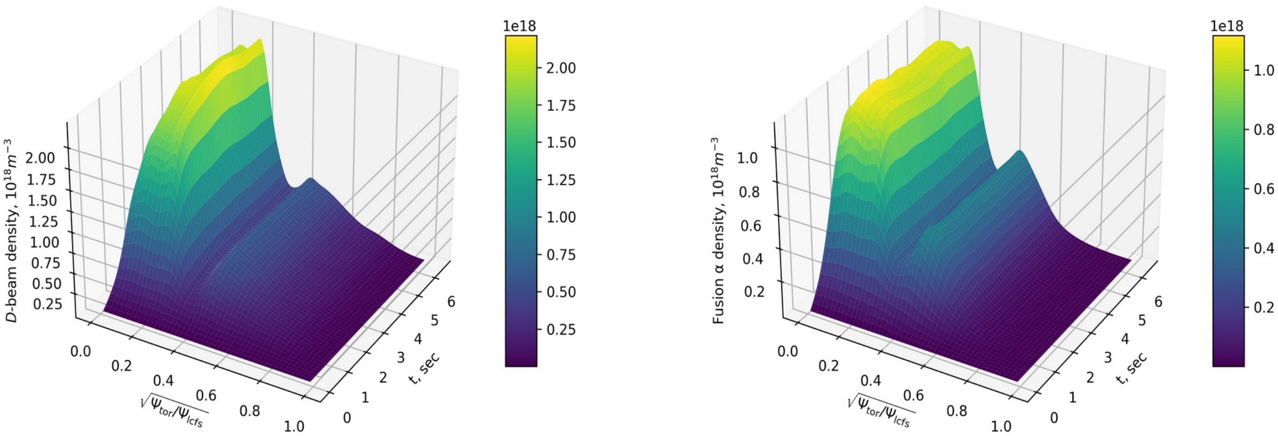

Fig. 1. *The contour maps of beam ion (left) and fusion alpha particles (right) density profile evolutions shown at different time starting (t,sec) from application of RBQ computed AE diffusion coefficients presented as function of fast ion minor radius (* $\sqrt{\psi_{tor}/\psi_{lcfs}}$ *where* ψ_{tor}, ψ_{lcfs} *are the values of the toroidal magnetic flux and its value at the last closed surface, lcfs).*

The microturbulence can have a strong effect on AE saturation by broadening the phase-space locations near the WPI resonances [9]. As a result the AE amplitudes can reach values from 10^{-4} up to 10^{-3} and higher for AEs in ITER whereas no significant fast ions losses to the wall are found [3].

In the final stage, the standalone NUBEAM package [8] is applied to evolve the fast ion distribution functions in the COM space. We have found that the classical EP confinement does not lead to much of fast ion losses, which is consistent with earlier studies. The 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 scenarios without quantitative predictions of turbulence levels.

We have found though that the beam ions injected at 1MeV lead to stronger growth rates to excite AEs in comparison with fusion alpha particles, born with the isotropic source. In contrast, the background microturbulence can enhance EP losses in ITER plasmas by broadening the WPI resonance regions which needs to be studied further.

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