Suppression of ion-scale turbulent transport by MeV-range fast ions at JET

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The success of ITER and future fusion power plants crucially relies on reaching self-sustained burning plasma conditions through fusion-born alpha particle heating. Therefore, it is of paramount importance to demonstrate that the achieved thermal energy confinement is sufficient to generate enough alpha particles and subsequently that those alpha particles at very high energy (3.5 MeV) are well confined to self-sustain the total reaction. Nevertheless, the physics of alpha particles is complex and the extrapolation from present knowledge not straightforward. Furthermore, the strong gradients in tokamak plasmas add an extra ingredient: the microturbulence which, other than limiting the overall performance of the device, may interact with the confinement of the highly energetic alpha particles leading to unexpected regimes. It is thus essential to explore experimental scenarios mimicking ITER conditions in order to gain deeper insights on the mutual interaction between alpha particles and microturbulence.

Recently at JET [1, 2], a series of experiments has been performed with the use of the three-ion heating scheme [3]. In particular, in the $(\mathrm{D}-\mathrm{D}_{\mathrm{NBI}}-{}^{3}\mathrm{He})$ scenario, deuterons are injected in the plasma by Neutral Beam Injection (NBI) system at energy $\sim$100 keV acting as the resonant absorber species, and thereby further accelerated to MeV range (up to $\sim$2.5 MeV) through the efficient application of the Ion Cyclotron Resonance Heating (ICRH) in the three-ion scheme.

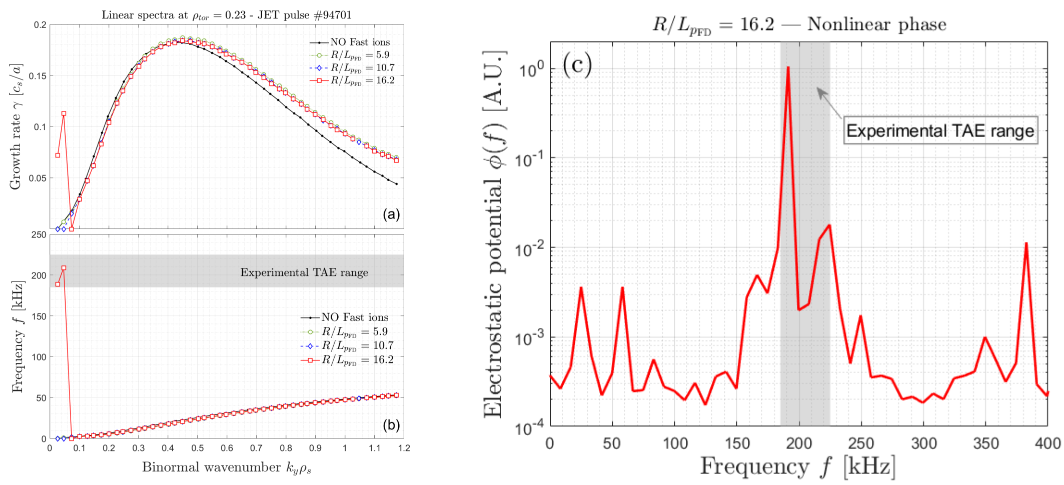

Figure 1: *Linear growth rates (a) and mode frequency (b) spectra computed by* GENE. *In (c), the frequency spectrum of the nonlinear electrostatic potential fluctuations for* $R/L_{p_{FD}} = 16.2$. *The grey shaded area in panel (b) indicates the frequency range at which TAEs are experimentally detected.*

Hence, such a substantial population of MeV-range fast ions well reproduce the fusion-born alphas' energy. The experimental outcomes of this scenario were surprising: although the strong electron heating in the core and the systematic excitation of a rich variety of Alfvén eigenmodes (AEs), both due to the produced fast ions, several experimental indicators show an improvement of the ion thermal confinement [1, 2, 4]. In fact, comparing the L-mode JET pulse #94701, in which the three-ion scheme generated MeV-ions, to the L-mode pulse #94704 at very similar experimental conditions, in which the same input power is provided only by NBI (fast ion energy $\sim$100 keV), diverse differences are found. The plasma energy content is enhanced in the three-ion scenario, as well as the neutron rate (almost by an order of magnitude).

Therefore, to obtain details on the underlying causes of this beneficial impact of MeV-ions, numerical analyses with the state-of-the-art gyrokinetic GENE code [5] in its flux-tube version have been carried out. The aforementioned JET pulse #94701 has been chosen as test-bed case, with the simulation box centered around the flux surface at $\rho_{tor} = 0.23$, since a significant population of MeV-ions [6] and the presence of toroidicity-induced AEs (TAEs) [4] are experimentally measured at that radial location. It must be clarified that the radial localization of TAEs have been measured with the X-mode reflectometer for JET pulse #95669, run at very similar conditions of pulse #94704, since for the latter such measurements were not available. The input data for GENE are provided by TRANSP integrated modelling applied to pulse #94701 at $t = 9.5$ s (details on the input parameters as well as numerical setup are given in Ref. [4]. Linear stability analyses are shown in Figure 1(a) and (b). Ion Temperature Gradient

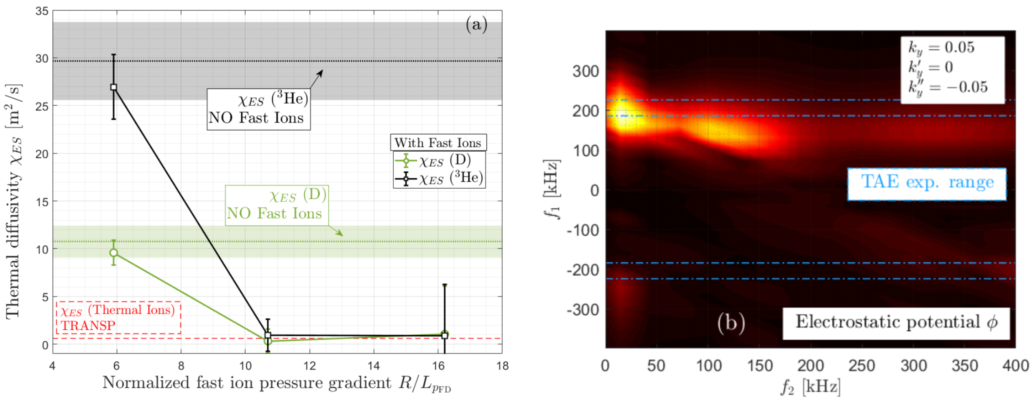

Figure 2: *(a) Electrostatic thermal diffusivities of D and* ^{3}*He as a function of* $R/L_{p_{\rm FD}}$*. (b) Wavelet bispectrum for the electrostatic field fluctuations of the considered triplet with* $R/L_{p_{\rm FD}} = 16.2$*.*

(ITG) mode is the dominant instability, peaking around the binormal wavenumber $k_y\rho_s = 0.45$, with ρ_s the Larmor radius at the sound speed. Fast ions linearly destabilize non-global dominant modes in the low-k_y region, with a frequency within the TAE experimental range of frequencies (185 kHz $\lesssim f \lesssim$ 235 kHz), when the normalized fast ion pressure gradient $R/L_{p_{\rm FD}} > 10.7$. Such modes, identified as fast-ion-driven TAEs, are also present in the nonlinear phase, as illustrated in Figure 1(c), which shows the spectrum of the perturbed electrostatic potential ϕ for $R/L_{p_{\rm FD}} = 16.2$ (for the marginally stable configuration $R/L_{p_{\rm FD}} = 10.7$, TAEs are nonlinearly destabilized similarly to Ref. [7]). It is also observed that no fast ion impact on the ITG stability is present in these numerical analyses, unlike previous studies [8, 9].

To assess turbulence dynamics and the impact of fast D ions on the thermal transport, nonlinear simulations have been performed, scanning over $R/L_{p_{\rm FD}}$. The electrostatic heat diffusivities χ_{ES} of both bulk ion species (thermal D and ^{3}He) are shown in Figure 2(a). The thermal ion diffusivity is strongly reduced when a critical value in $R/L_{p_{\rm FD}}$ is overcome. Such a threshold corresponds to the nonlinear destabilization of the fast-ion-driven TAEs. Importantly, when the suppression of the bulk ion transport occurs, a quite good agreement with the TRANSP power balances illustrated by the horizontal red dashed lines in Figure 2(a) is achieved. The complex interplay between the FI-driven TAEs and the nonlinearly generated Zonal Flows (ZFs) is envisaged to be the underlying mechanism responsible for the suppression of the electrostatic component of the thermal ion heat fluxes. Chosen as a figure of merit, the zonal flow shearing rate $\gamma_{E\times B} \equiv |k_x^2\phi(k_y = 0, k_x)|$ is almost doubled when the fast ion pressure gradient is large enough to destabilize TAEs. Thus, the radially sheared ZFs suppress the ITG-driven transport by de-correlating the turbulent eddies. Moreover, a bispectral analysis based on the wavelet decomposition in time [10] has been carried out to evaluate the possible nonlinear multi-mode coupling between the zonal and the TAE spatio-temporal scales. The amplitude of the wavelet bispectrum of the electrostatic potential for the triplets $(k_y\rho_s, k_x\rho_s) = (0.05, 0)$ (TAE peaking), $(k'_y\rho_s, k'_x\rho_s) = (0, a)$ (ZF scale) and $(k''_y\rho_s, k''_x\rho_s) = (-0.05, -a)$, with a considering all the retained k_x modes, is shown in Figure 2(b) for the TAE saturation phase. A dominant structure thus emerges at the crossing between the TAE and ZF frequency ranges, demonstrating the strong coupling between TAE and ZF wavenumbers. These findings are consistent with recent theoretical studies about the TAE-forced-driven generation of zonal structures [11]. Because of the increase of the zonal component amplitude of ϕ with unstable TAEs, such a coupling suggests a net energy transfer from the TAE to the ZFs scales. The same bispectral analysis has also been performed for the magnetic potential $A_{\|}$ leading to analogous results, indicating that the TAE destabilization leads to a strong nonlinear coupling between TAE and ZF scales for both fields [4].

In conclusion, for the first time in a validation study, the described complex multi-scale mechanism triggered by the externally generated MeV ions in the three ion scenario at JET is shown to lead to the ion-scale turbulence suppression, in the presence of a strong AE activity and core electron heating. These promising results represent a further step towards the full exploitation of alpha-heated fusion devices such as ITER.

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