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Exploring New Frontiers of the Ion-Scale Turbulence Suppression by Fast Ions

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One of the main causes of the energy confinement degradation in tokamak plasmas is represented by microturbulence. Therefore, for the success of ITER and future fusion devices, the reduction of microturbulence-induced transport reveals of prime importance. In the last decade, an improvement of the thermal confinement in the presence of a significant population of fast ions (FIs) generated by ICRH or NBI power has been observed in several tokamak devices **[1,2,3,4]**. These experimental observations were confirmed by the subsequent numerical analyses **[5,6]** up to a critical threshold in the total plasma pressure coinciding with the full destabilization of large-scale and high-frequency FI-driven modes **[7]**. In this framework, recent gyrokinetic simulations pointed out that such FI-modes actively help in reducing the ITG transport by boosting the zonal flow (ZF) activity, but only when marginally stable **[8]**. The present comprehensive study addresses two still elusive points by, firstly, extending the FI effect beyond the critical pressure threshold in ITER-relevant conditions, and secondly, by exploring turbulence regimes different to ITG.

An ITER-relevant scenario has been recently developed at JET by means of the efficient application of the 3-ion heating scheme **[9]**, which generated a substantial population of MeV-range ions. In spite of the rich variety of Alfvén Eigenmodes (AEs) excited by the MeV-ions, the thermal confinement is improved **[10]**. For the first time in a validation study, the detailed gyrokinetic numerical analyses unveiled a complex mechanism leading to ion-scale turbulence suppression in the presence of MeV-ions **[11]**, whose modelling closely mimic the characteristics of the alpha particles in an ITER predicted scenario **[12]**. Such a suppression is obtained only in conditions of unstable FI-driven TAEs, in good agreement with the experimental measurements. In-depth multi-mode analyses reveal that TAE spatio-temporal scales nonlinearly couple to the zonal fluctuations of the electrostatic perturbed field, triggering thus a strong zonal shearing activity which suppresses the ITG turbulent transport. Such a zonal shearing activity is less effective on TEM-driven transport **[13]**. Therefore, numerical analyses on the impact of NBI-generated FIs in a TEM-dominated JT-60U high-β discharge has been performed in order to study their impact on different turbulent regimes. It is shown that the TEM-driven fluxes are not affected by the FI presence, up to a critical pressure threshold. Beyond such a threshold, the turbulence pattern is dominated by FI modes which lead to an explosion of the fluxes, consistently with previous studies of low-energetic FIs on ITG, but not with the here reported 3-ion scenario at JET.

Hence in the present study, the combination of experimental and numerical evidences shows that the beneficial FI effect in reducing the ITG-driven turbulence has been extended up to MeV range of FI energy, suggesting that a similar behavior could be expected also in ITER and alpha-heated plasmas. However, some possible restrictions may be encountered in the dominant turbulence regimes, for which the reported complex mechanism could not be effective.

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