HOW MEV-RANGE IONS AND HIGH β WILL SHAPE THE CORE PLASMA DYNAMICS OF FUSION POWER PLANTS

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Next-generation tokamaks and future fusion power plants will operate with high-β plasmas dominated by fusion-born α-particle heating, where core plasma dynamics are shaped by complex burning plasma physics. MeV-range ions, high-β, micro-turbulence, large- and meso-scale perturbations of the electromagnetic fields, and their nonlinear interplay, will regulate this inherently out-of-equilibrium system. However, current tokamaks, operating primarily in pure Deuterium (D) at relatively low temperatures, cannot fully replicate these conditions. In fact, the fast ions are generated through external heating systems at a much lower energy than α particles (~100 keV vs. 3.5 MeV), making the destabilization of Alfvén Eigenmodes (AEs) and related high-β electromagnetic effects on turbulence and confinement challenging to study.

This contribution explores key physical mechanisms critically influencing core transport and confinement properties in tokamak plasmas, with implications for future fusion reactors. Indeed, some of this reactor-relevant physics has been recently explored experimentally and theoretically, unveiling a very complex multi-scale interaction occurring among fast ions and background turbulence which has a crucial positive impact on the overall confinement and performances [1]. Moreover, the fundamental wave-particle interaction occurring at high-β plasmas is responsible of distortions in the electron distribution function (EDF), with a direct impact on the temperature measurements through routinely used diagnostics [2]. Eventually, Deuterium-Tritium (DT) campaign at JET has enriched our understanding of burning plasma conditions extending insights from pure D plasmas [3].

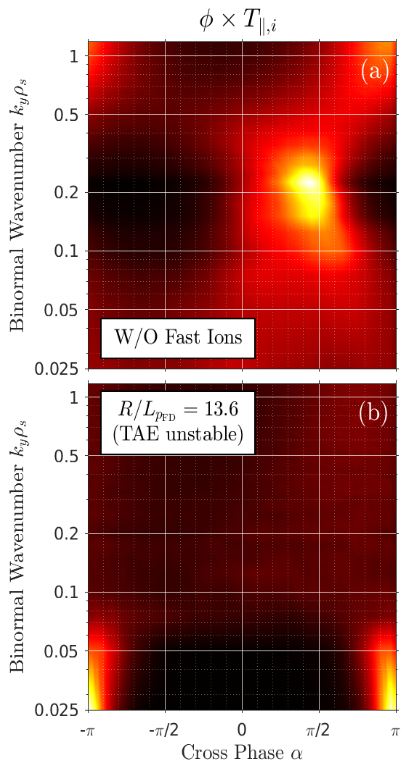

Fig. 1: Simulated cross-phase between electrostatic potential and parallel ion temperature fluctuations without fast ions (a) and with unstable TAE (b).

A nonlinear multi-scale mechanism triggered by MeV-range ions and leading to turbulence suppression in the plasma core of L-mode JET plasmas has been recently unveiled through experimentally validated gyrokinetic simulations [1,3], in a multi-code (GENE [4] and CGYRO [5]) effort. Such highly energetic ions destabilize Toroidal Alfvén Eigenmodes (TAEs) that couple to the axisymmetric perturbations of both electrostatic and magnetic potentials. Such a coupling, verified through bicoherence analysis against experimental measurements [6], leads to an energy transfer from the TAEs to the zonal structures, whose de-correlating effects on the ion-scale turbulence is strongly enhanced in such conditions. Interestingly, the turbulence suppression is achieved only when the local fast-ion pressure gradients is large enough to destabilize the TAEs. Additionally, the cross-phase of heat-flux-related quantities is analyzed in the context of turbulent transport suppression dynamics. **Fig. 1** demonstrates this beneficial transition from an out-of-phase state ($\pi/2$) to an in-phase state (π) at the TAE-dominated wavenumbers, confirming the suppressed transport in the presence of unstable TAEs. An upper limit is, however, found due to the steep increase of TAE-induced electromagnetic fluctuations, leading to unrealistic electron fluxes, restraining thereby the achievable TAE amplitude.

These results sparked interest on the optimum plasma state achieved through this fast-ion-triggered mechanism, and thus further experiments in other tokamaks were performed to mimic those conditions. Similar nonlinear interplay, individuated through coherence multi-mode analyses is observed in theory-driven TCV pulses [5] and, importantly, also in DT plasmas at JET [3]. CGYRO simulations of JET DT pulses highlight the role of fast-ion-driven instabilities as a source of zonal perturbation increased activity, which is further enhanced by the isotope effect in DT compared to pure-D plasmas.

Such optimum plasma states at high high β were routinely reached in recent JET campaigns. In such conditions, a long-standing issue concerns the discrepancy between Electron Cyclotron Emission (ECE) and Thomson Scattering (TS) measurements, which could exceed 5 keV in ITER and, thus, impair the performance evaluation of burning plasmas. A recent heuristic model reconciled such discrepancy by introducing a bipolar perturbation in the EDF, affecting the EC emission/absorption spectra [2]. GENE gyrokinetic simulations of selected JET pulses identified core-localized Kinetic Ballooning Modes (KBMs) destabilized at high-β as the cause of this EDF perturbation. The fundamental wave-particle interaction, regulated by the diamagnetic frequency ω_e^* of the resonant electrons, impacts the EDF momentum phase-space, forming a bipolar structure that aligns with the heuristic model [8]. **Fig. 2** displays the computed perturbed EDF in the momentum space $(p_\parallel, p_\perp)$, with the bipolar structure centred at $\omega_e^* = 0$ and a maximum perturbation at the matching $\omega_e^* = \omega_{KBM}$ (the KBM linear frequency). Being the diamagnetic frequency related to the local electron temperature and density gradients, this analysis could inform future experimental studies on the perturbation detection, making the ECE a tool for turbulence characterization in the deep plasma core. The nonlinear interaction among the KBMs unveiled a clear relation between the amplitude of the KBM-induced turbulence and the strength of the perturbation.

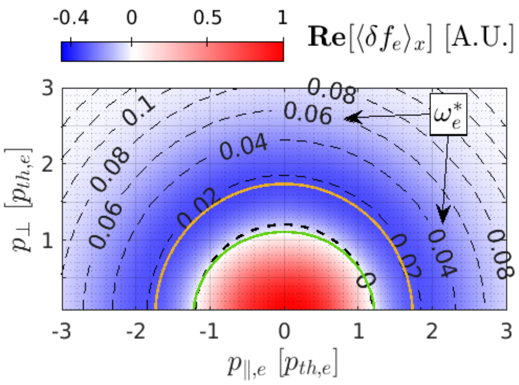

Fig. 2: Perturbed linear EDF in momentum space of a KBM-dominated wavenumber with clear bipolar structure. ω_e^* is plotted above with dashed lines. Green and gold curves correspond to $\omega_e^* = 0$ and $\omega_e^* =$

This contribution provides, therefore, a comprehensive exploration of the complex dynamics involving turbulence, high-β electromagnetic fluctuations and highly energetic particles in the plasma core of future tokamaks.

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