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Turbulence suppression due to energetic particles: From first principles to gyrokinetic simulations and experimental observations

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ITB formation due to energetic particles. The performance of present-day and future fusion devices is largely determined by turbulent transport generated by plasma turbulence. Any mechanisms able to reduce the overall radial propagation of energy and particles is, therefore, crucial in view of scenario optimization. This contribution presents numerical results of turbulence suppression by supra-thermal ions and experimental results from ASDEX Upgrade, which support these numerical findings. More precisely, the simulations demonstrate, for the first time, the generation of an internal transport barrier (ITB) triggered purely by energetic particles in a monotonic safety factor configuration.
Physical mechanisms. These results are explained in terms of a resonant interaction between ion-driven turbulence and supra-thermal particles, recently identified via gyrokinetic flux-tube simulations [1]. Fast ions have been found to interact with the plasma micro-instabilities through a wave-particle resonance mechanism when the fast ion magnetic-drift frequency is close to the linear frequency of the ion temperature gradient (ITG) microinstability, thus amplifying an otherwise negligible interaction. A theoretical analysis and numerical simulations have shown that the flow of such a resonant energy exchange is determined by the fast particle temperature, density and their gradients and, in turn, sets the direction of the fast ion energy losses. Inward (outward) supra-thermal ion particle and heat fluxes are observed in correspondence with the strongest fast ion stabilization (destabilization). Therefore, in a radially global setup, stabilizing (inward fluxes) and destabilizing (outward fluxes) energetic particle effects on plasma turbulence occur at different radial positions - depending on the local values of the fast particle parameters - thus strongly affecting the bulk ion energy fluxes.
Gyrokinetic GENE simulations. In this contribution, we significantly extend the previous findings - based on flux-tube analyses - by means of global electromagnetic GENE [2] simula-tions with kinetic electrons (realistic proton-electron mass ratio) and a sophisticated bi-Maxwellian model for the energetic particle distribution. The main results are displayed in Fig.1, where the time evolution of the radial profile of the (surface averaged) ion heat flux is shown for the simulations without (left plot) and with (right plot) energetic particles.

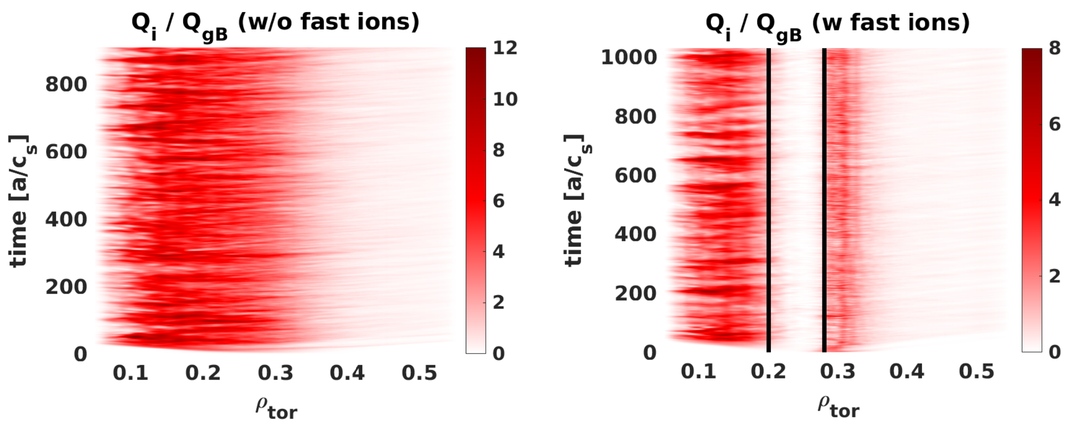

Figure 1: Nonlinear ion heat flux in GyroBohm units for the GENE global simulations a) without and b) with energetic particles. The vertical black lines denote the lower and upper radial boundaries of the internal transport barrier triggered only by energetic particles.

Fig.1 shows – to our knowledge - the first numerical evidence of an ITB generated solely by the energetic particles. In particular, a full suppression of ITG-driven turbulence is observed in the radial domain \rho_{tor}=[0.2,0.3]. As the turbulent heat flux drops in the ITB region, a corresponding increase of the neoclassical transport is observed. However, the resulting overall flux remains at significantly lower levels compared to the case without energetic particles. The same magnetic equilibrium and kinetic profile of the main plasma are employed in both the simulations regardless the presence of the supra-thermal ions, thus excluding e.g. any effects of the geometry on the generation of the ITB. These results are fully consistent with the physical picture of the wave-particle resonant interaction summarized above. More precisely, due to the local changes in the fast ion temperature and density profiles, the effect of supra-thermal particles on plasma turbulence turns from stabilizing in \rho_{tor}=[0.2,0.25] to destabilizing in \rho_{tor}=[0.25,0.3]. Thus, reverting the sign of the energetic particle energy flux from inward to outward. This sharp change in the direction of the fast ion heat flux strongly affects the shearing rate levels. Localized shearing layers are generated in correspondence of the negative inward and positive outward fast particle heat flux, thus tearing apart the radially elongated ITG eddies and resulting in the first ITB solely triggered by energetic particles.

Experimental evidence. These predict-first numerical results led to the design of an ASDEX Upgrade discharge [3] where this resonant interaction between ITG-driven turbulence and supra-thermal ions was maximized via gyrokinetic GENE simulations. The energetic particle profiles have been calculated with the code TORIC/SSFPQL [4]. A substantial increase of the peaking of the main ion temperature (Ti) profile of the order of ~80% is observed (as shown in Fig. 2) in the radial domain where the resonant interaction is predicted to be maximized. Such a relevant Ti is obtained via on-axis (\rho_{tor}=0) ion-cyclotron-resonant-frequency (ICRF) heating of the H minority species in D plasmas, with a large H concentration of n_H/n_e ≈ 0.11. Furthermore, no degradation of the energy confinement is observed during a ramp-up of the ICRF power, thus suggesting a substantial reduction of the anomalous turbulent transport. More specifically, a power balance analysis reveals a central region of improved confinement as the ICRH power is increased. The resulting radial heat flux profiles obtained with global GENE simulations exhibit the same features as in Fig. 1. The overall fluxes (including the neoclassical contribution) are in agreement with the experimental power balance only in the presence of energetic particles.

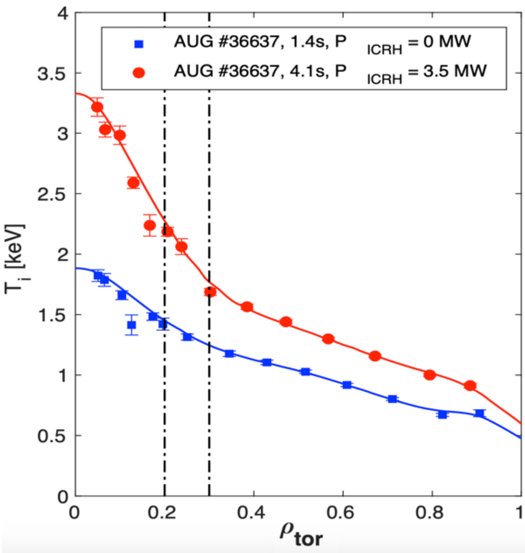

Figure 2: Main ion temperature profiles measured for the ASDEX Upgrade discharge #36637 at t=1.4s (blue line) with no ICRF heating and at t=4.1s (red line) with an ICRF power of 3.5MW. The vertical black lines denote the position of the ITB in the GENE global simulations.

Conclusions. This contribution provides, for the first time to our knowledge, numerical results that energetic particles can effectively trigger internal transport barriers in realistic tokamak configurations. These findings are supported by experimental evidence at ASDEX Upgrade and represent an essential step forward to access unique and still unexplored high confinement regimes.

References

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