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Turbulence stabilization due to high beta and fast ions in high-performance plasmas at ASDEX Upgrade and JET

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**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

High-performance fusion plasmas are desired to reach high plasma beta. Yet, the dependence of the thermal confinement time on this important parameter is unclear: Dedicated experiments yielded inconclusive results [1] and most theoretical results are obtained in simplified setups (overview e.g. in Ref. [2]). Using high accuracy plasma parameter measurements and realistic geometry for recent H-mode discharges at ASDEX Upgrade and JET (with ITER-like-wall), turbulent transport is studied by means of GENE gyrokinetic simulations in the plasma core.

Electromagnetic effects in plasma microturbulence

The gyrokinetic simulation code GENE is developed for studying microturbulence in strongly magnetized plasmas, such as fusion plasmas. In this work, we use the local flux-tube version of GENE [3]. Finite values of $\beta = 8\pi p_0/B_0^2$ allow for electromagnetic effects, which are characterized into two types, dynamic and geometric. Self-consistent perpendicular ($\tilde{A}_{||}$) and parallel ($\tilde{B}_{||}$) magnetic fluctuations account for dynamical β effects. Geometric β effects are related to pressure-induced changes in the magnetic equilibrium and thus the magnetic drifts. When the fast ion pressure p_{fast} constitutes a significant fraction of the total pressure, contributions to both electromagnetic effects are expected.

A pair of ASDEX Upgrade discharges varying β

In the ASDEX Upgrade discharges #29197 (case A, $\beta_N = 1.67$) and #29224 (case B, $\beta_N = 2.6$), β_e varies by a factor of two at mid-radius, while changes in other dimensionless parameters, such as $\rho^\star$ and $\nu^\star$, as well as magnetic geometry are by far less pronounced [2].

At the reference position of $\rho_{tor} = 0.5$, both plasmas appear unstable to ion temperature gradient (ITG) modes and microtearing modes (MTMs). As seen in Fig. 1(a) for case B, ITG is stabilized and MTMs become more unstable at higher β_e. Kinetic ballooning modes (KBM) are not expected to play a role for transport, since the experimental value of β is at 40% of the KBM threshold for case B and 20% in case A. In Fig. 1(b), the gyrokinetic results on thermal transport are compared to the power balance computed with the TRANSP code [5]. In these simulations, magnetic flutter transport (that would be expected from MTM turbulence) is negligible, even though ITG and MTM can exhibit comparable growth rates. Thus, ITG turbulence reduction is the dominant β effect. The resulting nonlinear up-shift of $a/L_{T,\mathrm{crit}}$ increases with beta, which is in agreement with previous results obtained for simplified setups [4]. Due to the high stiffness in the simulation results, these findings are within the experimental uncertainty. However, the trend of higher gradient at higher beta is consistent between experiment and gyrokinetic modelling in the plasma core. The experimental finding of degrading global confinement $\tau_E B_0 \sim \beta^{-0.2}$ (although weaker than the IPB(y,2) result $\tau_{E98y2} B_0 \sim \beta^{-0.9}$) is thus likely attributed to pedestal physics.

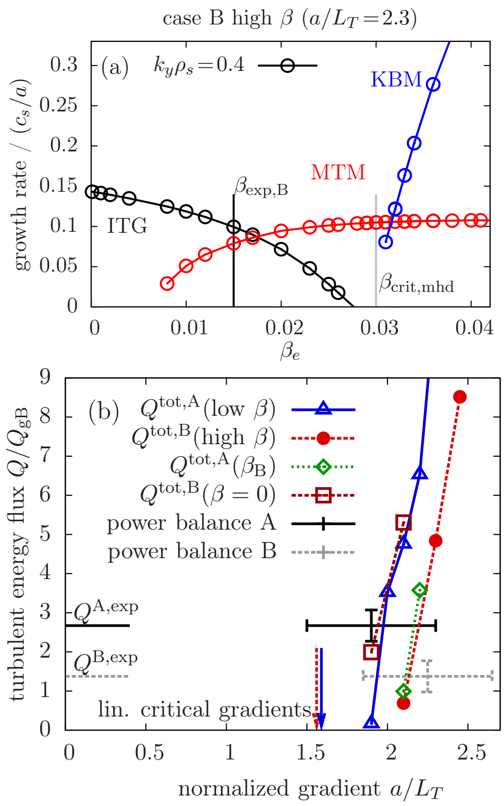

Figure 1: *(a) Growth rates as a function of β_e for a selected k_y (case B) at $\rho_{tor} = 0.5$. (b) Turbulent heat transport from GENE simulations compared to the power balance results.*

A power scan at JET-ILW in hybrid mode

In the following, we analyze two discharges from a power scan in a low triangularity hybrid configuration at JET: #84798 (low power LP) and #84792 (high power HP). To explain the measured weak power degradation of confinement and increasingly peaked ion temperature in the core, a fast ion induced positive feedback between edge and core has been proposed [6, 7]: Increased core pressure due to β-stabilized turbulence improves pedestal stability by an increased Shafvanov-shift, which in turn elevates the core profiles and further increases β. The virtuous cycle is stopped once β_{crit} for the instability of KBM (or fast particle driven modes, like beta induced Alfvén eigenmodes BAE) is reached and strong fast particle transport sets in.

Figure 2 shows the growth rate of the most unstable mode for both JET plasmas at $\rho_{tor} = 0.33$.

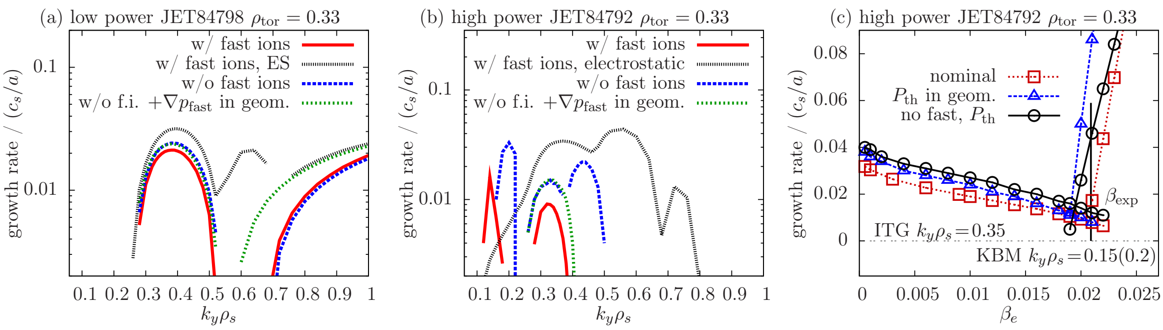

Figure 2: *Wavenumber spectra for JET discharges 84798 (a) and 84792 (b) at* $\rho_{\mathrm{tor}} = 0.33$. *(c)* β_e *scan in the HP case, we select* $k_y\rho_s = 0.35$ *for ITG and, to capture* β_{crit}, $k_y\rho_s = 0.15$ *for nominal case KBM and* $k_y\rho_s = 0.2$ *otherwise.*

The nominal case is compared to the following reduced setups: (1) electrostatic (with fast ions), (2) neglected fast ions in dynamics and geometry, (3) neglecting fast ions in dynamics, but retaining their pressure contribution to the equilibrium. Indeed, while electromagnetic effects are somewhat stabilizing for the low power case and fast ions play a minor role, these have greater impact for the high power case. Here, the nominal β is close to β_{crit}, which is rather low due to low magnetic shear, and ITG growth rates are strongly reduced due to mostly dynamic β effects. The ratio $\beta/\beta_{\mathrm{crit}}$ has been demonstrated to be a good measure for the degree of ITG turbulence reduction [8]. A transition to higher harmonic tearing parity ITG [9] is not observed, but may be triggered by even larger ∇p_{fast}. In the present case, geometric stabilization due to p_{fast} has little effect on ITG, but shifts β_{crit} upwards by about 10%, as depicted in Fig. 2(c).

Figure 3 shows an a/L_{Ti} scan of GENE turbulent ion heat transport in comparison to power balance results. For the high power discharge, the experimental operation point lies between the strongly stabilized ITG regime and KBM/BAE turbulence. In the KBM/BAE turbulence regime, thermal transport for fast particles and electrons generally is large and more stiff than ion thermal transport, which is expected to set a limit on the electron and fast particle temperature gradients.

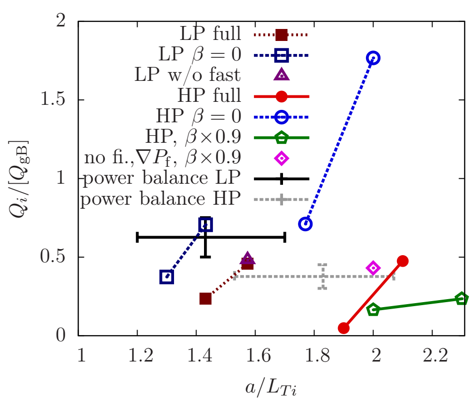

Figure 3: *GENE turbulent transport as a function of* a/L_{Ti}*, compared to power balance results. for JET #84798 (low power) and #84792 (high power).*

In view of future experimental validation beyond the match of macroscopic quantities (like Q_i), GENE turbulence data is characterized in greater detail. Distinctions between turbulence types are made by real frequency (or phase velocity) and cross phase relations. As an example, we observe the $n \times \phi$ phase angle close to zero for electrostatic ITG and about π for KBM turbulence. Idealized KBM (interchange) turbulence exhibits a cross phase of $\pi/2$ only [10, 11]. Furthermore, it will be helpful to compare turbulence correlation lengths and times with reflectometry measurements.

Summary and Conclusions

Electromagnetic effects in fusion plasmas play an increasingly important role, as β_{crit} is approached. In the present ASDEX Upgrade beta scaling experiment in standard H-mode, $\beta/\beta_{\mathrm{crit}}$ does not exceed 40%. Also the threshold for strong MTM transport is not overcome, despite substantial growth rates in the linearized system. Thus, increased core confinement is expected due to ITG turbulence reduction at higher beta. The global confinement time is degrading weakly $\tau_E B \sim \beta^{-0.2}$ in this set of experiments, however.

In the JET hybrid H-mode power scan, one finds $\beta \approx \beta_{\mathrm{crit}}$ at high power, especially in the very core of the plasma, where magnetic shear is low. Including a fast ion dynamic species contributes to dynamic electromagnetic ITG turbulence reduction and this effect is very strong in the high power case. These results support the hypothesis of a fast particle induced positive feedback between core and edge stability towards high beta, which has been invoked to explain weak power degradation also in comparable C-wall JET hybrid plasmas.

Overall, our results indicate that turbulence stabilization due to increased beta and/or fast particles contributes to improved plasma confinement, providing a tool for the optimising future experiments.

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