Gyrokinetic turbulence simulations of high-β plasmas

M.J. Pueschel[1,2], H. Doerk[1], T. Görler[1], F. Jenko[1]

[1] *Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany*

[2] *Max-Planck-Institut für Sonnensystemforschung, D-37191 Katlenburg-Lindau, Germany*

Abstract

Different tokamak core turbulence scenarios are investigated with respect to the β dependence of the transport, and a strong amplification of the Dimits shift is found for ITG turbulence. Moreover, radially global runs show moderate deviations from the local limit for mid-size experiments. Lastly, nonlinear microtearing simulations are presented, focusing on transport and magnetic fluctuation levels.

In recent, dedicated experiments, researchers have obtained exponents for the scaling of the plasma confinement time τ_E with the normalized plasma pressure $\beta \equiv \beta_{\rm e} = 8\pi n_{\rm e0} T_{\rm e0}/B_{\rm ref}^2$ (with electron density $n_{\rm e0}$ and temperature $T_{\rm e0}$, as well as equilibrium magnetic field $B_{\rm ref}$). The results, however, vary strongly, ranging from very little or no dependence (DIII-D) [1] to $\tau_E \propto \beta^{-0.9}$ (ASDEX Upgrade) [2] and even $\tau_E \propto \beta^{-1.4}$ (JET) [3], highlighting the need for a deeper understanding of the properties of finite-β transport phenomena. By presenting results from gyrokinetic electromagnetic simulations, the present work aims to shed some light on some of these properties. First, previous studies [4] are extended by new parameter regimes [5], thus providing β scans for the most relevant core microturbulence scenarios. Generally, zonal flow dynamics play a major role in determining the nonlinear transport, and for the ion temperature gradient (ITG) case, a strong increase of the Dimits shift with β is observed. Second, (radially) global simulations with finite β are presented, corroborating the applicability of local runs to the bigger present-day and to future experiments. Lastly, nonlinear simulations of the microtearing (MT) mode are discussed, along with their magnetic transport, and the corresponding coefficient for the amplitude of magnetic fluctuations is reported.

The GENE Code

All simulations presented here were performed with the gyrokinetic Vlasov code GENE [6]. In its linear mode, this code may also be run as an eigenvalue solver, giving access to subdominant and stable modes; it can be operated radially locally as a flux tube code or globally; and it is publicly available.

Next, different operation points are used to study the impact of finite-β effects both on the linear modes – including the onset of kinetic ballooning modes (KBMs) – and the turbulent transport. Details on the physical and numerical settings can be found in Ref. [5].

TEM Turbulence

The left plot in Fig. 1 shows the linear growth rate γ of the trapped electron mode (TEM) as a function of β for multiple toroidal wave numbers k_y (in units of the inverse ion sound gyroradius ρ_s^{-1}). A small stabilizing effect with increasing β can be observed. The KBM threshold β_{crit} is determined by the low-k_y range—a corresponding analysis yields $\beta_{\text{crit}} \approx \beta_{\text{crit}}^{\text{MHD}} = 2.03\%$.

Nonlinearly, however, the picture changes (see Fig. 1, right plot): with increasing β, the transport grows steadily. This can be explained by a diminished role of zonal flows in the nonlinear saturation process: zonal flows are known to inhibit transport [7] and to decrease in strength with β. It is also to be noted that the nonlinear KBM threshold agrees very well with the linear prediction.

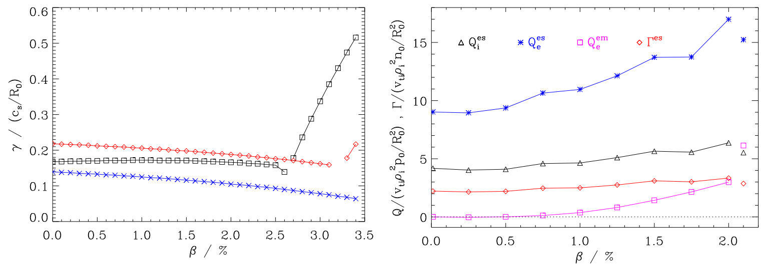

Figure 1: TEM case: Linear growth rates (left) for $k_y = 0.2, 0.4, 0.6$; and nonlinear transport (right).

ITG Turbulence

To avoid the complications that arise (mostly due to mode interaction) when performing and analyzing electromagnetic Cyclone Base Case [8] simulations [4], the parameters of the ITG mode investigated here were chosen for the mode not to interact with other instabilities. In the left plot of Fig. 2, the stabilizing effect of β on γ is visible (with $\beta_{\text{crit}} = 1.8\%$, significantly deviating from the MHD value $\beta_{\text{crit}}^{\text{MHD}} = 2.44\%$).

Qualitatively, this result carries over to nonlinear runs, but the stabilization occurs much faster in the latter, see the right plot in Fig. 2—while the KBM threshold agrees also quantitatively with its linear counterpart. The deviation in the transport behavior can again be explained by the zonal flow dynamics: since here, the growth rate declines more strongly than the zonal flow strength, the relative influence of the zonal flows grows with β, resulting in lower transport.

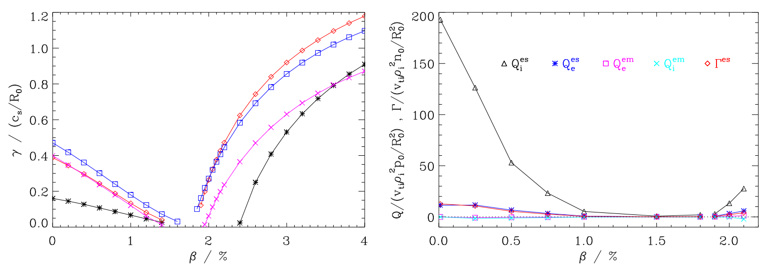

Figure 2: ITG case: Linear growth rates (left) for $k_y = 0.1, 0.2, 0.3, 0.4$; and nonlinear transport (right).

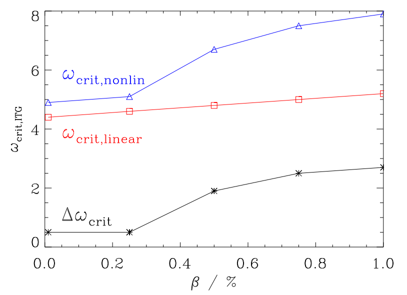

Figure 3: Linear/nonlinear critical gradients and Dimits shift as functions of β for the ITG case.

One can also observe this effect in the critical gradients. As shown in Fig. 3, the so-called Dimits shift [8], i.e., the nonlinear upshift of the critical ion temperature gradient, increases significantly at moderately high β. It is to be noted that the relatively sudden increase from $\beta = 0.25\%$ to 0.5% is not accompanied by qualitative changes in other standard diagnostics such as the spectra.

Non-Local Effects

To assess the influence of radially non-local effects, GENE was operated linearly in its global mode (see, e.g., Ref. [9]) at Cyclone-like parameters. As shown in Fig. 4, finite $\rho^* \equiv \rho_{\rm ref}/a$ (with a denoting the minor radius) simulations agree qualitatively with the local limit $\rho^* \to 0$. From the figure, it can be inferred that only small experiments should observe strong deviations from that local limit, and that ITER-sized machines will, at least in the core, almost certainly be described well by local physics alone.

As a consequence of the above results, it is no surprise that standard local properties of electromagnetic simulations carry over: ITG stabilization, largely unaffected TEMs, and eventually KBMs—note that the KBM threshold hardly varies over a large range of ρ^* values.

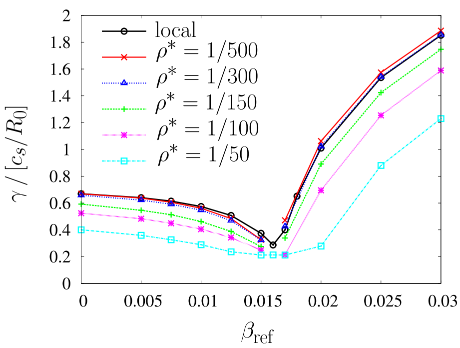

Figure 4: Growth rate at $k_y = 0.28$ as a function of β for different values of ρ^* for Cyclone-like parameters.

Microtearing and Magnetic Fluctuations

Recently, microtearing (MT) modes have received increased attention, in part because they tend to appear subdominantly in many finite-β studies (see, e.g., Ref. [10]). Fig. 5 shows results from first nonlinear MT simulations: namely, the dependence of the transport on the magnetic fluctuation strength. Clearly, the (quadratic) curve follows the standard model investigated in Ref. [4] based on an ansatz detailed in Ref. [11].

The magnetic fluctuation strength $\tilde{B}_x/B_{\rm ref}$ can also be used to determine the redistribution of fast particles in turbulent magnetic fields [12]. Thus, it is helpful to specify coefficients to describe the fluctuation amplitude: $\tilde{B}_x/B_{\rm ref} = \mathscr{C}_x(\beta/\beta_{\rm crit})(\rho_{\rm i}/R_0)$, with the major radius R_0. While it was found previously [5] that ITG turbulence tends to have $\mathscr{C}_x \sim 0.8$ and TEM turbulence $\mathscr{C}_x \sim 0.2-0.4$, the corresponding result for MT obtained here is $\mathscr{C}_x \sim 0.2$.

Ref. [13] originally predicted $\tilde{B}/B_{\rm ref} \sim \rho_e/L_{Te}$, with the electron temperature gradient length L_{Te}. In the present simulations, this result is retained correctly, albeit the underlying assumption $\gamma \propto k_y^2$ is found not to be fulfilled.

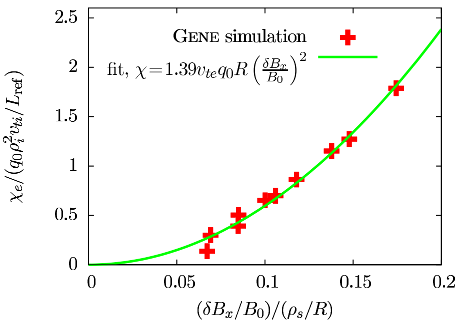

Figure 5: Nonlinear microtearing simulations: magnetic part of the electron heat diffusivity as a function of the magnetic fluctuation strength.

Summary

In this work, a variety of finite-β studies was presented. Generally, TEM and ITG turbulence exhibits qualitative differences from the respective linear modes, and in both cases the β-modified strength of the zonal flows with respect to the linear growth rate can explain the deviations. For the ITG scenario, a study of the critical gradients reveals a strong amplification of the Dimits shift, significantly extending the nonlinear stability regime. Global simulations are used to corroborate the applicability of local runs to the larger present-day and future experiments, while physically accurate descriptions of mid-size machines may require radially global studies. Lastly, first nonlinear microtearing results are used to show good agreement with a standard magnetic transport model, as well as to extend a previously reported list of coefficients describing the amplitude of magnetic fluctuations in turbulent simulations.

References

[1] C.C. Petty et al., 45th Annual Meeting of the APS Division of Plasma Physics, Albuquerque, USA (2004)

[2] L. Vermare et al., Nucl. Fusion **47**, 490 (2007)

[3] D.C. McDonald et al., 35th EPS Conference on Plasma Physics, Hersonissos, Greece (2008)

[4] M.J. Pueschel, M. Kammerer, and F. Jenko, Phys. Plasmas **15**, 102310 (2008)

[5] M.J. Pueschel and F. Jenko, submitted to Phys. Plasmas (2010)

[6] `http://www.ipp.mpg.de/~fsj/gene/`

[7] P.H. Diamond, S.-I. Itoh, K. Itoh, and T.S. Hahm, Plasma Phys. Control. Fusion **47**, R35 (2005)

[8] A.M. Dimits et al., Phys. Plasmas **7**, 969 (2000)

[9] T. Görler, Ph.D. thesis, Universität Ulm (2009)

[10] D. Told et al., Phys. Plasmas **15**, 102306 (2008)

[11] A.B. Rechester and M.N. Rosenbluth, Phys. Rev. Lett. **40**, 38 (1978)

[12] T. Hauff, M.J. Pueschel, T. Dannert, and F. Jenko, Phys. Rev. Lett. **102**, 075004 (2009)

[13] J.F. Drake, N.T. Gladd, C.S. Liu, and C.L. Chang, Phys. Rev. Lett. **44**, 994 (1980)