GENE simulations on the beta dependence of tokamak core turbulence

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Abstract

The scaling of heat transport in tokamak experiments with the normalized plasma pressure $\beta$ is the subject of ongoing discussion. We investigate the matter by performing linear and nonlinear gyrokinetic simulations using the GENE code. In addition, first results in JET geometry are presented.

Introduction

A number of tokamaks have performed scaling experiments in which the normalized plasma pressure $\beta$ was varied. High $\beta$ is fundamental both for fusion reaction rates and the bootstrap current. However, reported scaling exponents of the normalized energy confinement time $- B\tau_E \propto \beta^\alpha$ differ widely, from $\alpha = 0$ for JET [1] and DIII-D [2] to $\alpha = -0.9$ for ASDEX Upgrade [3] and $\alpha = -1.4$ for JET [4]. In order to get a better understanding of that property, one can use computer models, varying $\beta$ while keeping all other parameters constant. Simulations have to include both ion and electron species, and consider magnetic field fluctuations in order to capture finite-$\beta$ effects. Such simulations have been performed by various groups both on the gyrofluid [5, 6] and on the gyrokinetic side [7, 8, 9]. In the present work, we employ GENE [10, 11], an electromagnetic flux tube code that solves the gyrokinetic Vlasov equation self-consistently with the corresponding field equations. It is designed to run in any local MHD equilibrium geometry, using explicit 4th order Runge-Kutta time stepping, and operating in Fourier space both in toroidal as well as in radial direction. A comprehensive review of gyrokinetic theory can be found in [12].

Numerical parameters

The point of operation is chosen on the basis of the Cyclone Base Case, as defined in [13]. A $101.78 \times 125.66$ perpendicular box employs 192 radial modes of both positive and negative sign (24 for linear simulations), and 24 positive toroidal modes. The normalized gradients responsible for driving the turbulence are $R/L_{Ti} = R/L_{Te} = 6.9$, and $R/L_n = 2.2$. For the ion-electron mass ratio, hydrogen was chosen. $\beta$ is defined as $8\pi n_e 0 T_{ref}/B_{ref}^2$, where $n_e 0$ is the electron density, $T_{ref}$ the normalization temperature, and $B_{ref}$ the magnetic field.

Linear results

Figure 1: Growth rate and frequencies as a function of $\beta$. GS2 [15] values obtained for verification show very good agreement with GENE results.

Linear simulations were performed at $k_y = 0.2$, which is close to the maximum in the nonlinear transport spectra. Since the Cyclone Base Case was designed to study ion temperature gradient (ITG) modes, these are dominant for low $\beta$. As $\beta$ is increased, the ITG growth rate is reduced, and at a value of $\beta_{\text{crit,TEM}} = 0.01$, trapped electron modes (TEM) surpass the ITG modes (see Fig. 1). As predicted by MHD for ideal ballooning modes, at a threshold $\beta_{\text{crit,KBM}} = 0.013$, ballooning modes become dominant, more specifically their kinetic variant (KBM). However, it is to be considered that KBMs become unstable even before that point, and remain subdominant for a short while. To determine that point, we switched from the initial value solver to its eigenvalue counterpart which is also available in GENE [14]. Fig. 2(a) shows how the KBM growth rate behaves around the critical point $\beta_{\text{crit}} = 0.0114$. Note that the MHD prediction for that value is $\beta_{\text{crit,MHD}} = 0.01344$.

A noteworthy detail is that while in kinetic theory, a finite $k_y$ results in a downshift of the critical $\beta$, it can be seen that this shift is not very big, and that for smaller values of $\beta$, the modes becomes fully stable. Consequently, it is unlikely that nonlinearly, these modes are excited well below the $\beta$ threshold.

Nonlinear results

Nonlinearly, the ITG branch of the electrostatic ion heat flux $Q_{\text{es}}^i$ (see Fig. 2(b)) shows a very similar behavior to the linear growth rate: a steady decline with increasing $\beta$ can be observed. Also noteworthy is the fact that while $Q_{\text{es}}^i$ is getting smaller, $Q_{\text{es}}^e$ remains roughly constant, and $Q_{\text{em}}^e$ becomes increasingly important. However, at $\beta \approx 0.008$, some new mechanism seems to kick in and cause a decrease in the electron fluxes.
Figure 2: (a): Growth rate of the kinetic ballooning mode as a function of $\beta$. (b): Saturated heat and particle flux values as functions of $\beta$. For large $\beta$, the fluxes drop to lower levels than one would expect from the linear physics.

Application to JET geometry

As the $\delta$-$\alpha$ geometry is a strong approximation of a real tokamak equilibrium, especially in high $\beta$ shaped plasmas, it is interesting to study the $\beta$ dependence of turbulence in a realistic geometry. This has been performed in the conditions of a JET discharge (#68595) which is part of the recent dedicated $\beta$ scan experiment (see [4]). The normalized parameters taken at mid-radius are $\beta = 0.0105, R/L_n = 1.4, R/L_{Te} = 4.8, R/L_{Ti} = 5.8, q = 1.6, \delta = 1.1$, and $T_i/T_e = 0.86$. The triangularity is relatively high ($\delta = 0.4$), as well as the Shafranov shift which compresses the magnetic surfaces on the low field side. The TRACER code [16] was used to reconstruct the geometry of a flux tube according to this equilibrium.

Nonlinear simulations were performed in this configuration for four different $\beta$ values covering the experimental range: $\beta = 0.0085, 0.0105, 0.0112$, and $0.012$. Fig. 3(a) shows a very weak dependence of the ion and electron heat fluxes over this range of $\beta$. This clearly contrasts with the experimental observation of a strong degradation of confinement with increasing $\beta$, but agrees with a fluid modeling which suggests that this experimental degradation is due to a mismatch in the dimensionless parameters [4]. It is also worth mentioning that, in contrast with simulations in $\delta$-$\alpha$ geometry, the electromagnetic contribution is negligible compared to the electrostatic fluxes.

Linear and nonlinear scans in normalized ion temperature gradient $R/L_{Ti}$ were also performed around the experimental value ($R/L_{Ti} = 5.8$) in order to identify a threshold ($R/L_{Ti}$)$_{crit}$ from which ITG modes start to drive turbulence. Fig. 3(b) indicates, as a function of $R/L_{Ti}$, the growth rate of the most unstable mode from the linear scan as well as the ion and electron electrostatic heat fluxes from three nonlinear runs. The accurate identification of a critical value
Figure 3: (a): Ion ($Q_i$) and electron ($Q_e$) electrostatic (ES) and electromagnetic (EM) heat fluxes as a function of $\beta$, after full saturation of nonlinear simulations. (b): Linear and nonlinear scans of the normalized ion temperature gradient: the linear growth rates indicate a threshold $\left( \frac{R}{L_{Ti}} \right)_{\text{crit}} \approx 3.6$ whereas the fit from nonlinear heat fluxes suggests $\left( \frac{R}{L_{Ti}} \right)_{\text{crit}} \approx 4.7$.

from the linear scan is difficult because of a knee around $\frac{R}{L_{Ti}} = 5$, but one could consider $\left( \frac{R}{L_{Ti}} \right)_{\text{crit}} \approx 3.6$ as a realistic value. In any case, the value identified from the nonlinear simulations, $\left( \frac{R}{L_{Ti}} \right)_{\text{crit}} \approx 4.7$, appears to be larger than the linear threshold. This is in agreement with the so-called Dimits shift first reported in [13].

Summary

The present work represents a first step into the high-$\beta$ regime which is numerically challenging but necessary to investigate if one is to compare simulations with experiments. Close to $\beta_{\text{crit}}$, the GENE results exhibit a substantial drop of the heat flux, which cannot fully be explained with linear physics. For JET discharge #68595, we find that the resulting ITG turbulence is subject to a Dimits shift but only weakly dependent on $\beta$ (keeping all other simulation parameters fixed).

References