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ABSTRACT.

The scaling of heat transport in tokamak experiments with the normalized plasma pressure β 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.

1. INTRODUCTION

A number of tokamaks have performed scaling experiments in which the normalized plasma pressure β was varied. High β 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 b 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- b 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 equillibrium 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].

2. NUMERICAL PARAMETERS

The point of operation is chosen on the basis of the Cyclone Base Case, as defined in [13]. A 101.78×125.66 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 $R/L_{\mathrm{Ti}} = R/L_{\mathrm{Te}} = 6.9$, and $R/L_n = 2.2$. For the ion-electron mass ratio, hydrogen was chosen. β is defined as $8\,\pi ne0T_{\mathrm{ref}}/B^2_{\mathrm{ref}}$, where n_{e0} is the electron density, T_{ref} the normalization temperature, and B_{ref} the magnetic field.

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 β. As β is increased, the ITG growth rate is reduced, and at a value of $\beta_{\mathrm{crit,TEM}} = 0.01$, Trapped Electron Modes (TEM) surpass the ITG modes (see Fig.1). As predicted by MHD for ideal ballooning modes, at a threshold bcrit,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 $\beta_{\mathrm{crit}} = 0.0114$. Note that the MHD prediction for that value is $\beta_{\mathrm{crit,MHD}} = 0.01344$.

A noteworthy detail is that while in kinetic theory, a finite k_y results in a downshift of the critical

β, it can be seen that this shift is not very big, and that for smaller values of β, the modes becomes fully stable. Consequently, it is unlikely that nonlinearly, these modes are excited well below the β threshold.

3. NONLINEAR RESULTS

Nonlinearly, the ITG branch of the electrostatic ion heat flux Q_i^{es} (see Fig.2(*b*)) shows a very similar behavior to the linear growth rate: a steady decline with increasing b can be observed. Also noteworthy is the fact that while Q_i^{es} is getting smaller, Q_e^{es} remains roughly constant, and Q_e^{em} becomes increasingly important. However, at $\beta \approx 0.008$, some new mechanism seems to kick in and cause a decrease in the electron fluxes.

4. APPLICATION TO JET GEOMETRY

As the $\hat{s}$ - α geometry is a strong approximation of a real tokamak equilibrium, especially in high β shaped plasmas, it is interesting to study the β dependence of turbulence in a realistic geometry. This has been performed in the conditions of a JET discharge (Pulse No: 68595) which is part of the recent dedicated β scan experiment (see [4]). The normalized parameters taken at midradius are $\beta = 0.0105$, $R/L_n = 1.4$, $R/L_{Te} = 4.8$, $R/L_{Ti} = 5.8$, $q = 1.6$, $\hat{s} = 1.1$, 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 β 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 β. This clearly contrasts with the experimental observation of a strong degradation of confinement with increasing β, but agrees with a fluid modeling which suggests that this experimental degradation is due to a mismatch in the dimensionless paramaters [4]. It is also worth mentioning that, in constrast with simulations in $\hat{s}$ - α 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 tubulence. 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 from the linear scan is difficult because of a knee around $R/L_{Ti} = 5$, but one could consider $(R/L_{Ti})_{crit} \approx 3.6$ as a realistic value. In any case, the value identified from the nonlinear simulations, $(R/L_{Ti})_{crit} \approx 4.7$, 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-β regime which is numerically challenging but necessary to investigate if one is to compare simulations with experiments. Close to bcrit, the

GENE results exhibit a substantial drop of the heat flux, which cannot fully be explained with linear physics. For JET Pulse No: 68595, we find that the resulting ITG turbulence is subject to a Dimits shift but only weakly dependent on β (keeping all other simulation parameters fixed).

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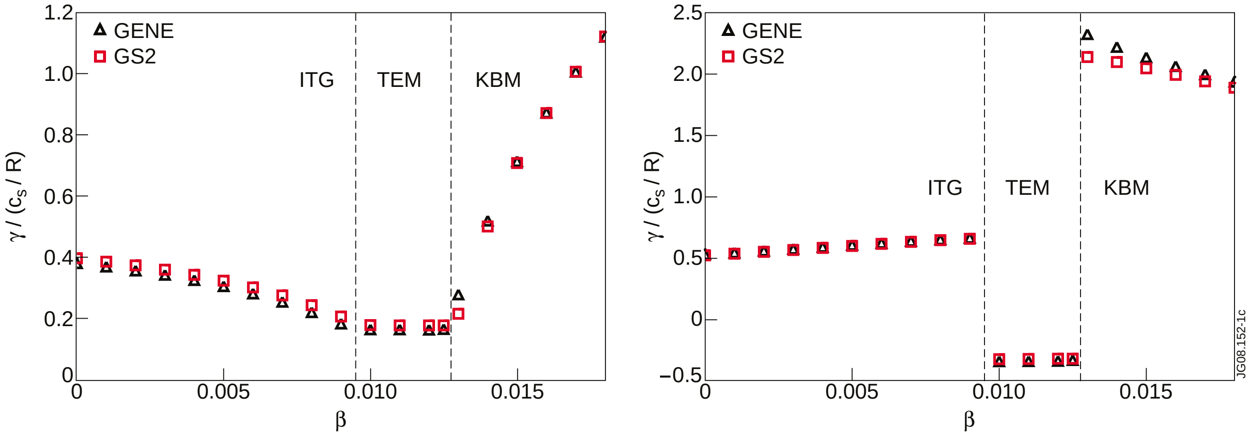

Figure 1: Growth rate and frequencies as a function of β. GS2 [15] values obtained for verifi- cation show very good agreement with GENE results.

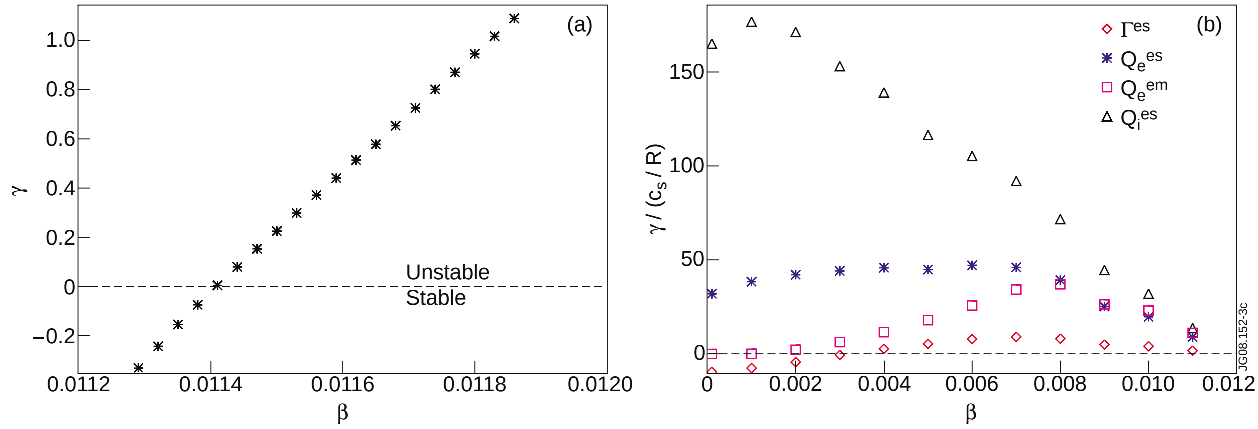

Figure 2: (a): Growth rate of the kinetic ballooning mode as a function of β. (b): Saturated heat and particle flux values as functions of β. For large β, the fluxes drop to lower levels than one would expect from the linear physics.

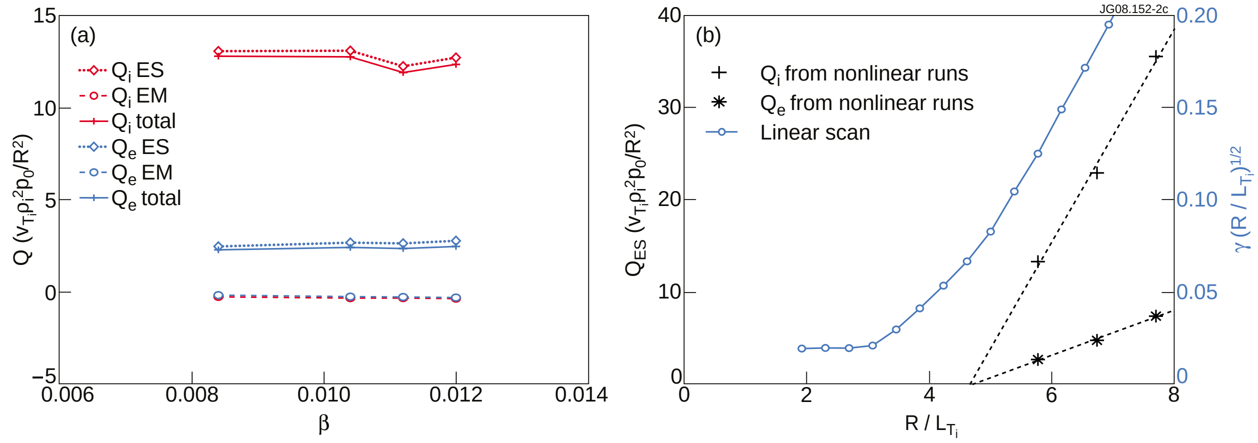

Figure 3: (a): Ion (Q_i) and Electron (Q_e) ElectroStatic (ES) and ElectroMagnetic (EM) heat fluxes as a function of β, after full saturation of nonlinear simulations. (b): Linear and nonlinear scans of the normalized ion temperature gradient: the linear growth rates indicate a threshold $(R/L_{Ti})_{crit} \approx 3.6$ whereas the fit from nonlinear heat fluxes suggests $(R/L_{Ti})_{crit} \approx 4.7$.