

Effects of flow shear on the correlation length of drift wave turbulence.

J. Weiland¹, P. Mantica² and the JET-EFDA Contributors^{*}

1. Department of Earth and Space Sciences, Chalmers. University of Technology and Euratom-VR Association, S41296 Gothenburg, Sweden

2. Istituto di Fisica del Plasma CNR-EURATOM, via Cozzi 53, 20125 Milano, Italy

*See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea

Abstract

Experiments on JET¹ have shown that stiffness of ion energy transport above a threshold gradient is strongly reduced in the plasma core due to flow shear. Initially transport models had difficulties to reproduce this feature. Later TGLF² has reproduced the trend, particularly in the region of low normalized heat flux, i.e. near threshold³. Also Gyro⁴ simulations have been made but these are still uncertain. The experimental observations also indicated in more detail that it is the combination of high flow shear and small magnetic shear that leads to stiffness reduction. This naturally limits the region of stiffness mitigation to the interior of tokamaks³. Since flow shear stabilizes drift wave transport by damping out primarily long wavelength perturbations, it is obvious that it influences the correlation length. Thus it was natural to generalize our previous work on making the correlation length for drift waves parameter dependent to include also the effect of flow shear. This has now been implemented and is found to reproduce the experimental feature that stiffness is reduced for a combination of large flow shear and small magnetic shear. The reason is that for large magnetic shear the radial correlation length is determined primarily by magnetic shear, whilst for low magnetic shear it is determined by flowshear. The first results of this modified correlation length model show good quantitative agreement with experiment.

Introduction

The understanding of stiffness of transport in tokamaks is an outstanding issue. It was, in particular, emphasized in connection with the first theory based ITER simulations⁵ since the performance of ITER depends more strongly on the height of the edge pedestal for stiff models. Theory based models also usually differ strongly in stiffness^{5,6}. Thus this is an important issue for the understanding of turbulent transport in tokamaks. In present day tokamaks a new possibility, Internal Transport Barriers (ITB), for improving confinement has been widely studied. Since flowshear is generally associated with transport barriers, the question of stiffness in the presence of flowshear becomes important^{1,3}. As it turned out models with multiple modenumbers here were in better agreement with experiment than our previous model. In our model⁷ effects of the mode spectrum have been included by using a parameter dependent correlation length⁸. However, that did not include effects of flowshear. The purpose of the present work is to extend the model to include effects of flowshear on the correlation length.

Formulation

For demonstration we will here show our simplest ion thermal conductivity and how flowshear enters.

$$\chi_i = \frac{1}{\eta_i} \left(\eta_i - \frac{2}{3} - \frac{10}{9\tau} \varepsilon_n \right) \frac{(\gamma - \omega_{ExB})^3 / k_r^2}{(\omega_r - \frac{5}{3} \omega_{Di})^2 + (\gamma - \omega_{ExB})^2} \quad (1a)$$

Here using (1a) means using the Waltz rule^{9,10}. The method used in Ref 8 is to find the linearly fastest growing mode as a function of modenumber, as normalized by the drift frequency. However, that could clearly not give another correlation length if we first calculate the growthrate and then apply the Waltz rule. Thus we have to use the formulation in (1b) where

$$\gamma = \gamma(\omega_{ExB}) \quad (1b)$$

we apply the Waltz rule inside our linear solver. In that way flowshear also influences the eigenfunction¹¹. Once the relevant modenumber has been found, we may, however go back to using (1a).

The result obtained in Ref 8 was

$$k_\theta \rho_s = \sqrt{\frac{2 f_{ls}}{1 + T_i / T_e}} \quad (2a)$$

where

$$f_{ls} = \left(0.7 + \frac{2.4}{7.14q\hat{s} + 0.1} \right) FL \quad (2b)$$

and FL is a typical $(k_\theta \rho_s)^2$ usually taken as 0.1. Here $\hat{s} = \sqrt{2s - 1 + \kappa^2(s - 1)^2}$ indicates modification of magnetic shear S due to elongation κ . Other notations are standard.

The result (2) is the FLR that gives the largest linear growthrate, normalized by the drift frequency. This corresponds to the correlation length found early as a result of modecoupling simulations in the local limit^{12,13}.

We now performed extensive scans of the growthrate, normalized by the electron magnetic drift frequency using the method indicated in Eq (1b). Two characteristic scans are shown in Fig 1.

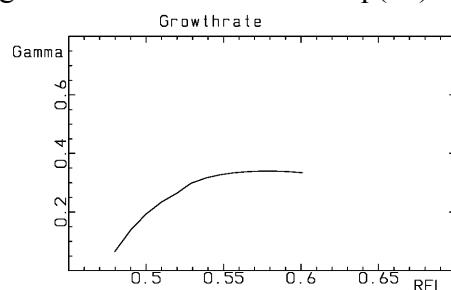


Fig 1a $S = 0.2$

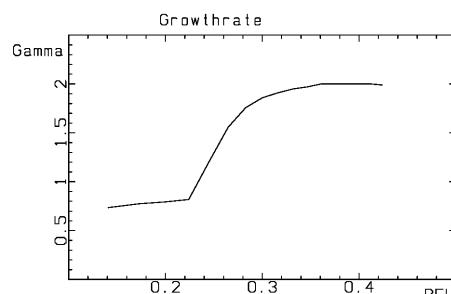


Fig 1b $S = 0.6$

Fig 1. Growthrate, Gamma normalized by the magnetic driftfrequency as a function of

$$RFL = k_\theta \rho_s$$

The other parameters were here $q=1.4$, $\epsilon_n=0.909$, $\eta_i=6.5$, $\kappa=1$ and $T_e=T_i$. Thus we used the Cyclone basecase⁶ for reference data and just varied S . The flowshear strength was

$$\hat{\omega}_{ExB} = \frac{\omega_{ExB}}{\omega_{De}} = 0.4$$

The result was:

$$fsl = \left(0.7 + RKK * |\hat{\omega}_{exb}| * (1 - |\hat{s}|)^2 + \frac{2.4}{7.14q\hat{s} + 0.1} \right) FL \quad (3a)$$

where

$$RKK = 4 + 3 * (\hat{s} - 0.2) / 0.2 \quad 4 + 3 * (\hat{s} - 0.2) / 0.2 \geq 0 \quad (3b)$$

$$RKK = 0 \quad 4 + 3 * (\hat{s} - 0.2) / 0.2 \leq 0 \quad (3c)$$

$$RKK = 0 \quad |\hat{s}| \geq 1 \quad (3d)$$

and we still use (2a) for the final result. Eq 3 expresses the fact that the correlation length is decreased (larger modenumber) due to flowshear as long as the magnetic shear is less than 1. For larger magnetic shear the correlation length is determined by magnetic shear. This trend is also clear from the scans in Fig 1. The previous q dependence also remains so that for larger q the new part due to flowshear gets more important. The limit $\hat{s}=1$ comes out numerically. Scans of the inverse correlation length normalized by gyroradius, $k_\theta \rho_s$ and the same basic Cyclone parameters as above are shown in Fig 2.

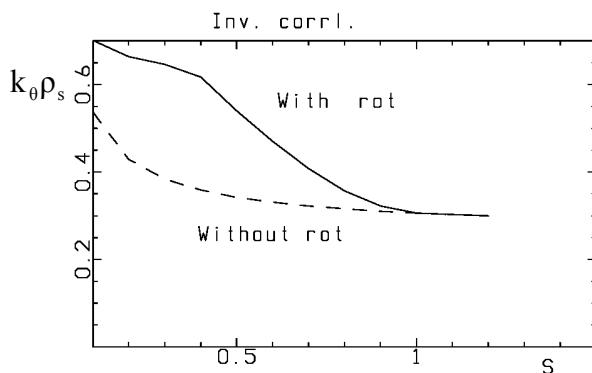


Fig 2a Inverse correlation length as a function of magnetic shear, $q=1.4$

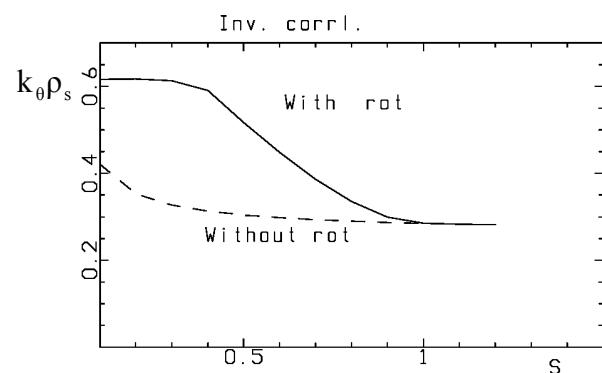
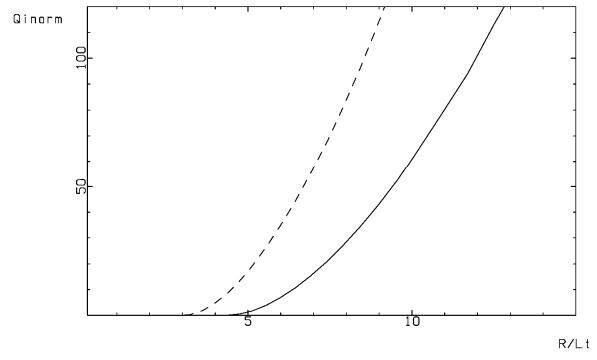
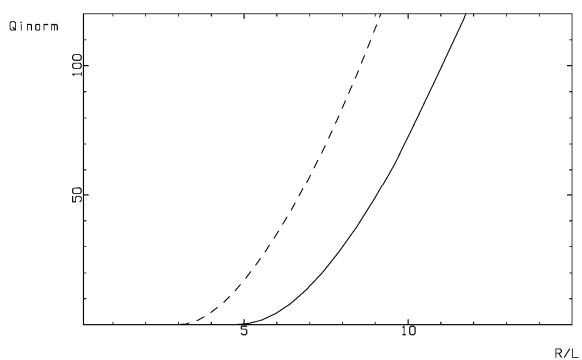


Fig 2b Inverse correlation length as a function of magnetic shear, $q=3$

We have then applied our transport code with the new correlation length to the JET experiment discussed in Ref 1. These are predictive runs for fixed parameters. Thus they are linear without Dimits shifts.



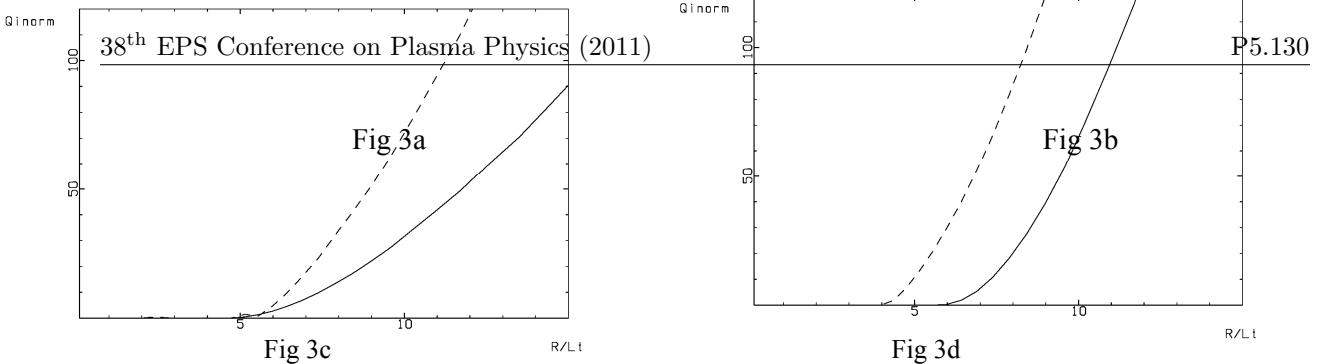


Fig. 3. Stiffness plots without rotation, dashed lines, and with rotation, full lines. Normalized flux (see ref 1) versus temp. grad. for the JET shot in Ref 1 at radial flux coordinate 0.33. The strength of rotation was $\gamma_E = \omega_{EXB}/(c_s/a) = 0.15$. The different figures show a) $s=0.57$, old model, b) $s= 0.57$, new model, c) $s=0.2$, new model and d) $s=1.2$, new model.

The results are as expected. The effect of flowshear on transport increases with the new reduced correlation length but the effect of correlation length on threshold is small as seen in Ref 11. This is shown by the difference between a) and b). The reduced magnetic shear in c) leads to lower stiffness while the increased magnetic shear in d) gives increased stiffness and the effect of flowshear gets larger with smaller s . The threshold without rotation is higher for small magnetic shear in d). This is due to averaging of the driving terms over the flatter modeprofile.

Discussion

The method of using a correlation length as the inverse wavelength of the fastest growing mode has turned out to reproduce the experimental trend of reduced stiffness in the presence of rotation very well. This choice is due to the fact that small eddies tear apart larger eddies so that the correlation length can normally not be much larger than the wavelength of the fastest growing mode. For shorter wavelengths the amplitude of oscillations usually decreases rapidly thus leaving eddies of the size of the fastest growing wavelength to dominate. This was seen already for turbulence simulations in slab^{12,13}. However, as pointed out in Ref 14, this principle is independent of the detailed geometry.

References

1. P. Mantica et. al. Phys. Rev. Lett. **102**, 175002 (2009).
2. G.M. Staebler et.al. Phys. Plasmas **14**, 055909 (2007).
3. P. Mantica et. al. A Key to Improved Ion Core Confinement in the JET Tokamak: Ion Stiffness Mitigation due to Combined Plasma Rotation and Low Magnetic Shear, 23rd IAEA Fusion Energy Conference, Daejeon, October 11-16 2010, EXC/9-2
4. J. Candy and R.E. Waltz, J. Comput. Phys. **186**, 545 (2003).
5. ITER Physics Basis Editors et al, Nucl. Fusion **39**, 2137 (1999).
6. A.M. Dimits, G. Bateman, M. Beer et. al. Phys. Plasmas **7**, 969 (2000).
7. J. Weiland, Collective modes in Inhomogeneous Plasma, Kinetic and Advanced Fluid Theory, IoP Bristol 2000.
8. J. Weiland and I. Holod, Phys. Plasmas **12**, 012505 (2005).
9. R.E. Waltz et. al. Phys. Plasmas **1**, 2229 (1994).
10. A. Zagorodny and J. Weiland, Phys. Fluids **16**, 052308 (2009).
11. J. Weiland, Phys. Plasmas **11**, 3238 (2004).
12. J. Weiland and H. Nordman, *Theory of Fusion Plasmas*, Proc Varenna – Lausanne Workshop (Chexbres, 1988) p 451 (1988).
13. H. Nordman and J. Weiland, Nucl. Fusion **29**, 251 (1989).
14. J. Weiland, *Turbulent Transport in Fusion Plasmas, Effects of Toroidicity and Fluid Closure*, Summer Collage on Plasma Physics August 10 – 29 (2009), International Centre for Theoretical Physics Trieste 2009.