Gyrokinetic simulations of mixing-length diffusivity on a High Field Spherical Tokamak (HFST)

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Introduction

The main advantages of operating a Spherical Torus (ST) compared to a conventional large aspect ratio tokamak are that: (1) along a field line there is a lot of good magnetic curvature (where the pressure gradient ∇p and curvature $\mathbf{b}\cdot\nabla\mathbf{b}$ point in the same direction) which stabilises MHD instabilities; (2) there is a naturally high elongation (κ) which allows for a high bootstrap fraction, meaning less current needs to be externally driven; (3) the plasma is stable with high currents, which means it is possible to have high densities as the Greenwald limit is higher; and (4) finally it is possible to have a high β and β_N. However, the drawback of the ST is that space within the centre column is limited which makes it difficult to fit in the blanket, shielding, cooling and central solenoid which would normally be required for a power plant. Consequently STs typically have a low magnetic field and conceptual designs for a ST power plant [1, 2, 3] (or Components Test Facility (CTF) [4]) have had to be very large (e.g. Culham ST Power Plant (STPP) $R = 3.4$m) in order to produce the required fusion energy (or neutron flux).

Recent advances in the manufacture of 2nd generation High Temperature Superconducting (HTS) material may make it possible to have a high magnetic field within a relatively small ST. This is mainly due to the reduction in cryogenic requirements. For example HTS material in a 5T magnetic field would have to be cooled to approximately 20K, compared to LTS which operates at 4K, this 16K difference represents a substantial engineering simplification.

It is worth nothing that some large aspect ratio tokamaks have operated with high magnetic fields, for example Alcator C-Mod ($A = 3$ and elongation 1.6 to 1.75) which operated with an on axis magnetic field of up to 8T (using copper coils) [5]. While this machine did observe slightly better confinement than the ITER scaling law would have predicted this improvement was relatively small. That being said experiments on MAST and NSTX suggest that confinement in an

ST depends more strongly on the magnetic field. However as the use of HTS materials in tokamaks is very new, with the GOLEM ($A = 4.7$) tokamak being the first to use HTS in 2012 [6], consequently HTS has not (to date) been used on an ST and this scaling law has not been verified. This motivates the current work which investigates how the combination of a previously impractical magnetic field along with low aspect ratio and high elongation affects the plasma confinement.

Linear gyrokinetic simulations

While non-linear gyrokinetics is the most desirable way to simulate the micro-stability of a plasma it is simply not feasible for large parameter scans. We therefore intend to perform many linear gyrokinetic simulations (using the GS2 code [7]) and later benchmark these against non-linear simulations. A measure of micro-stability is the mixing length γ/k_r^2 which is approximately equal to the diffusivity (χ), where γ is the growth rate and k_r is the mode's radial wave number ($k_r = \sqrt{n}\,(dq/dr)$). Using this as a measure of plasma confinement we intend to produce a scaling law which will describe how confinement on a flux surface depends on various local plasma parameters:

$$\chi = \chi\left(\beta, \nu_*, q, \varepsilon, \kappa, \delta, L_T, L_n, \hat{s}\right) \quad (1)$$

where β is the local (or flux surface average) plasma beta (i.e. $\beta = \iint_{\text{flux surface}} 2\mu_0 p/B^2 R\,dl\,d\phi / \iint_{\text{flux surface}} R\,dl\,d\phi$, where l is the poloidal arc length and ϕ the toroidal angle, note all other plasma parameters are averaged over the flux surface in the same manner); ν_* is the local collisionality normalised to the size of this flux surface; q is the safety factor; ε is the inverse aspect ratio of this flux surface (not the last closed flux surface); κ is the elongation of this flux surface; δ is the triangularity of this flux surface; L_T is the temperature gradient scale length (defined as $L_T = (1/T)\,|\partial T/\partial\rho|$, $\rho = r/a$); and L_n is the density gradient scale length, $\hat{s}$ is the magnetic shear. Note, we will not consider how the elongation gradient $\partial\kappa/\partial\rho$, triangularity gradient $\partial\delta/\partial\rho$, shift ($\Delta = d\,(R/a)\,/d\rho$ which is related to the derivative of the Shafranov shift) or flow shear (set to zero) affect the confinement, however we will keep these parameters constant. We also only consider the ideal case of a pure D-D plasma (i.e. $Z_{\text{eff}} = 1$), with the ion temperature equal to the electron temperature.

Table 1 shows two MHD equilibrium values, about which we shall perturb the plasma parameters to see how they effect the diffusivity. Figure 1 shows a plot of how the diffusivity (which we define as the largest γ/k_r^2 on a flux surface) depends on β, with red stars indicating case 1 plasma parameters and blue circles indicating case 2 plasma parameters were used. Note arbitrary units have been used for the diffusivity because our linear simulations have not yet been

	β	ν_*	q	ϵ	κ	δ	L_T	L_n	$\hat{s}$
Case 1	0.64	3.5	7.4	0.32	2.1	0.058	2.2	0.14	1.4
Case 2	42	0.59	0.71	0.29	1.9	0.024	2.0	0.67	1.4

Table 1: Shows two sets of local equilibrium parameters which we found by solving the MHD equations (using the SCENE code).

benchmarked against non-linear GS2 simulations or experimental data. However, we are mainly interested in the trend of how diffusivity depends on plasma parameters. From figure 1 we see increasing β (decreasing B) increases the diffusivity. We can also observe that this increase in diffusivity is not smooth and there is a jump which corresponds to a change in the dominant mode which we will show later. Previously we have shown the same trend by keeping all of the engineering parameters (e.g. pressure, temperature, etc) constant and simply increasing the magnetic field, however we found understanding these results to be problematic as all of the plasma parameters were free to vary.

Figure 2 shows the $k_y\rho_i$ mode spectrum of points A and B from figure 1. The dominant mode when the local plasma β is low (point A) has a high toroidal mode number (n), has twisting parity (the electrostatic potential is even) and is electrostatic. By contrast the dominant modes at higher β (poin B) have a lower toroidal mode number, tearing parity and are electromagnetic. Figure 3 shows how diffusivity depends on elongation, triangularity, safety factor and temperature scale length using the case 1 plasma parameters.

Conclusions

We find that when the local β is decreased below some critical value the dominant tearing modes are rapidly suppressed (leaving twisting modes) and the confinement is substantially improved. This opens the question: would it be sensible to operate a tokamka at a lower β than allowed by MHD stability in order to take advantage of the improved confinement.

In the future we intend to incorporate the scaling law into a time advancing transport code such as ASTRA to model a complete operating scenario.

References

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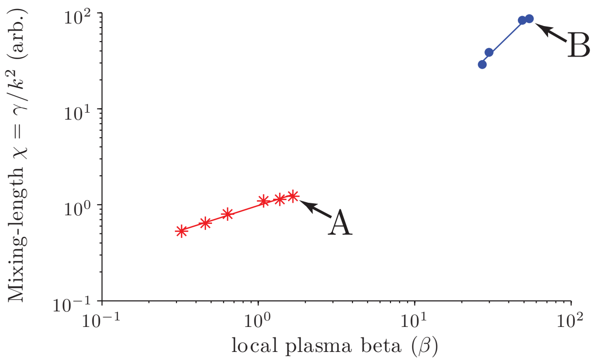

Figure 1: Shows how the mixing-length diffusivity depends on β. Red stars shows how diffusivity depends on β using case 1 plasma parameters (table 1) and blue circles show how diffusivity depends on β using case 2 plasma parameters. We have also labelled two points (A and B) which we show the $k_y\rho_i$ mode spectrum in figure 2.

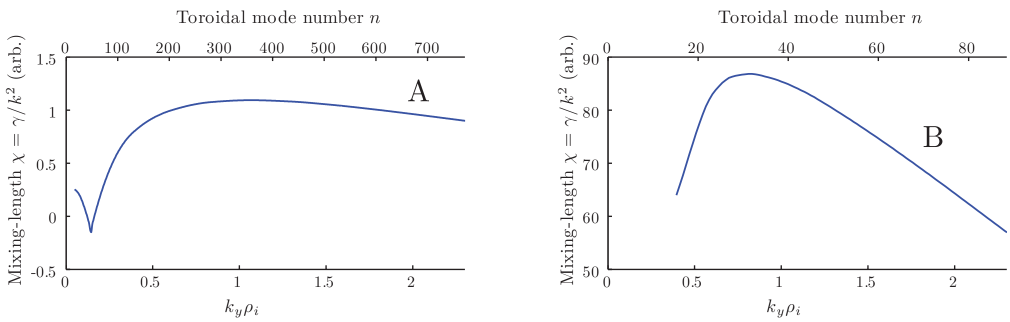

Figure 2: A and B show the $k_y\rho_i$ mode structure of points A and B in figure 1. We note that A has a higher toroidal mode number, has twisting parity and is electrostatic. By contrast B has a low toroidal mode number, has tearing parity and is electromagnetic.

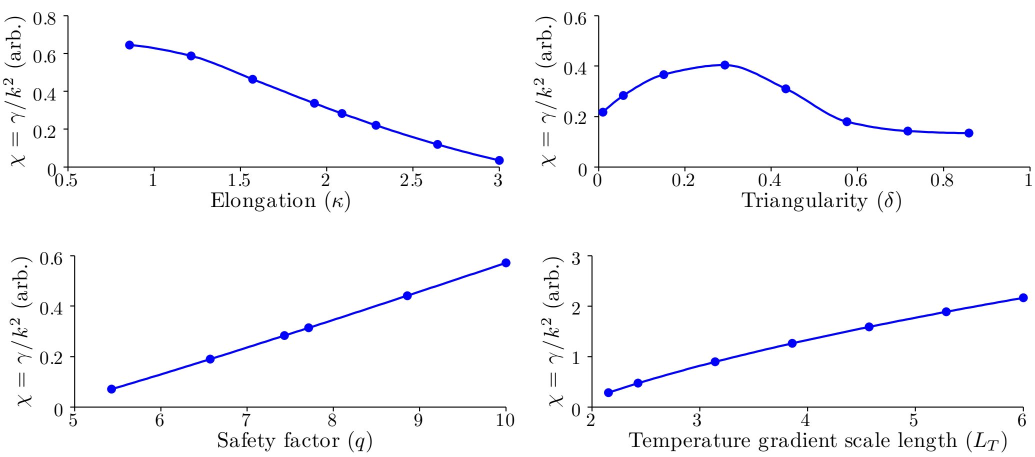

Figure 3: Show how the mixing-length diffusivity depends on elongation κ, triangularity δ, safety factor q and temperature gradient scale length L_T, using case 1 equilibrium plasma parameters (table 1).