Plasma confinement within 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 ($\kappa_{\max} \approx 2.4 + 65\exp(-A/0.376)$; [1]) which allows 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 finally (4) 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. Consequently STs typically have a low magnetic field and conceptual designs for ST power plants [2, 3, 4] (or Components Test Facilities (CTF) [5]) have been 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 [6], which potentially opens up a new mode of operation for STs. Recent system code results [7] have shown that the fusion performance gain (Q_{fus}) depends very strongly on the plasma confinement, and in particular the dependence of the energy confinement time (τ_{Eth}) on the plasma beta (β) strongly effects Q_{fus}. The IPB98(y,2) scaling law [8], was created from a free fit to the ELMy H-mode plasma confinement database, and has $B\tau_{\text{Eth}} \propto \beta^{-0.9}$. However, dedicated experiments [9, 10, 11] have not conclusively shown how τ_{Eth} depends on β: with some experiments showing no dependence (i.e. $B\tau_{\text{Eth}} \propto \beta^{0.0}$), while other, perhaps spurious, experiments show a weak dependence. As a result, so called beta independent scaling laws have been developed [10, 12, 11] which fit the experimental data almost as well as the IPB98(y,2) scaling. If the energy confinement time does not dependent on plasma beta then the extrapolation from present day experiments to pilot plants is far more favourable than the extrapolation using the

IPB98(y,2) scaling law.

Within this paper we will compare the confinement within a concept compact High Field Spherical Tokamak (HFST) operating in L-mode, to the high field ($B_T = 5.3$T) large aspect ratio ($A = 3.2$) Alcator C-Mod tokamak also operating in L-mode (shot #960301009, time 0.93 seconds). The purpose of this is to assess what effect the combination of ST geometry and high field has on plasma confinement, and we are particularly interested in the β dependence.

Methodology

Within this work we will explore how the core transport within Alcator C-Mod and our conceptual High Field Spherical Tokamak (HFST), depends on the local plasma beta (β), where in this context we define local to mean the flux surface where $r/a = 0.6$.

To do this systematically show what effect plasma beta has on the transport we must use the freedom we have in constructing the MHD equilibrium, using the SCENE code [13], to hold the most important local dimensionless parameters constant, whilst only allowing the plasma beta to change. In this work we have chosen to keep the shape of the last closed flux surface constant, as well as the following six local dimensionless parameters: (1) the normalised collisionality (ν_*), (2) the normalised gyro-radius (ρ_*), (3) the safety factor (q), (4) the magnetic shear ($\hat{s}$), (5) the inverse temperature scale length L_T^{-1}, and finally (6) the inverse density scale length L_n^{-1}.

Under these constraints to increase the plasma beta by a factor α requires: keeping the shape of the density profile constant, but increasing the absolute density by a factor α; keeping the shape of the temperature profile constant, but increasing the absolute temperature by a factor $\sqrt{\alpha}$; keeping the safety factor profile constant; and increasing the external magnetic field by a factor $\alpha^{\frac{1}{4}}$.

It is worth noting that we have not put any constraints on the current, or the geometry of the flux surface where $r/a = 0.6$ (i.e. the local κ, κ', δ, δ', R_0 and R_0'), as a consequence both the current profile and the shape of the flux surface will change as β changes.

The heat flux is calculated using the TGLF code [14], which we have benchmarked at various points against both linear and non-linear gyrokinetic simulations using the GS2 code [15].

Results

Table 1 compares the equilibria of the conceptual HFST to Alcator C-Mode (shot #960301009, time 0.93 seconds). We note that the main differences between the equilibria are that: (1) the collisionality is lower in Alcator C-Mode; (2) the normalised gyro-radius is lower on Alcator C-Mode; and (3) Alcator C-Mode has a larger major radius (higher aspect ratio). Because of the large difference between the two equilibria we are not particularly interested in the absolute

	Global parameters					Local parameters					
	R	a	κ	δ	T_{e0} (keV)	β (%)	ν_*	ρ_*	q	L_T^{-1}	L_n^{-1}
HFST	0.4	0.25	3.0	0.45	2.8	0.51	0.12	0.0055	4.7	2.21	0.68
Alcator C-Mode	0.69	0.22	1.6	0.45	4.1	0.75	0.05	0.0035	1.3	2.13	0.12

Table 1: Comparison between the conceptual High Field Spherical Tokamak (HFST) and Alcator C-Mode (shot #960301009, time 0.93 seconds).

level of the thermal diffusivity. Instead, we are interested in how the thermal diffusivity depends on the plasma beta, which is shown in figures 1 and 2. From these figures we note that the conceptual HFST is robustly beta independent, whereas the dependence of the thermal diffusivity within Alcator C-Mod on the plasma beta is far more complicated.

Conclusions

The thermal diffusivity within the conceptual HFST is almost independent of the plasma beta. However, under the conditions within the Alcator C-Mod (shot #960301009, time 0.93 seconds) the dependence of the thermal diffusivity on the plasma beta is far more complicated, with an increasing plasma beta resulting in an average improvement in confinement, which is the opposite to what the IPB98(y,2) scaling law would have predicted.

These results appear to support the experimental results which appear to indicate that the IBP98(y,2) scaling law does not have the correct beta exponent.

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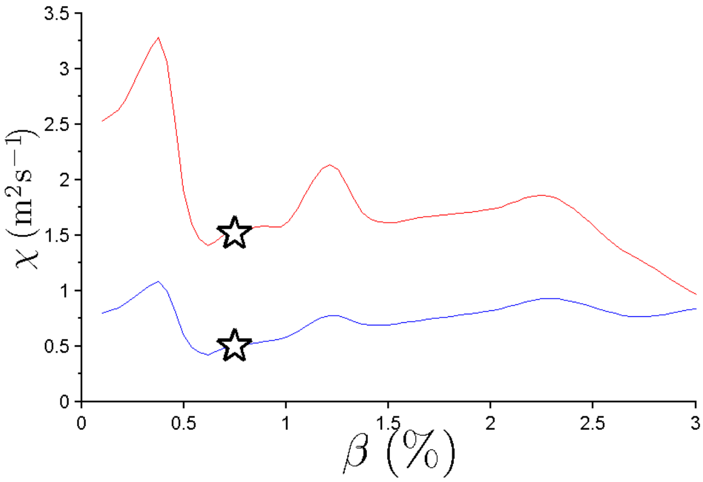

Figure 1: The thermal diffusivity within the conceptual High Field Spherical Tokamak (HFST), with red indicating ion and blue electron thermal diffusivity. The stars indicate the reference point as detailed in table 1. Note, we cannot increase the plasma beta any more as low n MHD modes then form.

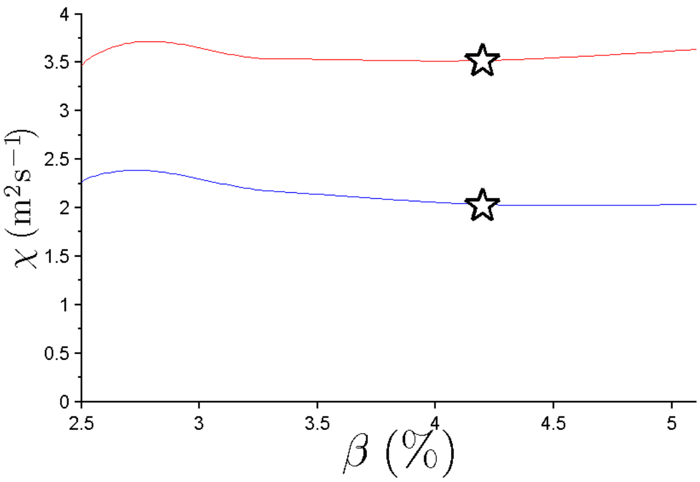

Figure 2: The thermal diffusivity within Alcator C-Mode (shot #960301009, time 0.93 seconds), with red indicating ion and blue electron thermal diffusivity. The stars indicate the reference point as detailed in table 1. Note, we cannot increase the plasma beta any more as low n MHD modes then form.