A PARAMAGNETIC NEARLY ISODYNAMIC COMPACT MAGNETIC CONFINEMENT SYSTEM

W.A. COOPER, J.M. ANTONIETTI
Centre de Recherches en Physique des Plasmas,
Association Euratom-Confédération Suisse,
Ecole Polytechnique Fédérale de Lausanne,
Lausanne,
Switzerland

T.N. TODD
UKAEA Fusion, Culham Science Centre,
UKAEA/Euratom Fusion Association,
Abingdon, Oxon,
United Kingdom

Abstract

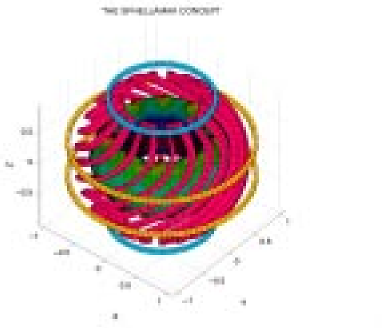
A coreless compact magnetic confinement system that consists of sets of helical windings and vertical magnetic field coils is investigated. The helical coils produce a small toroidal translation of the magnetic field lines and seed paramagnetism. The force-free component of the toroidal current strongly enhances the paramagnetism such that isodynamic conditions near the plasma centre can be approached. At $\beta \sim 5\%$, the configuration is stable to local MHD modes. Global MHD modes limit the toroidal current $2\pi J$ to about $-60kA$ for peaked J. Bootstrap-like hollow current profiles generate quasiaxisymmetric systems that require a close fitting conducting shell to satisfy external kink stability.

1. INTRODUCTION

The magnetohydrodynamic (MHD) equilibrium and stability properties of the Sphellamak concept [1] are investigated. The configuration is characterised by a combination of 10 helical coils wound on a sphere of $1m$. radius, has no central conductor and has a set of vertical field (VF) coils. A model with 4 filaments per coil is shown in Fig. 1a. The helical coils extend to a latitude of 60^o and are connected by circular arcs. They are modular with the currents flowing up a helical segment, across the upper connecting arc, then down the adjacent helical segment and then back across the lower connecting arc. This corresponds to a stellarator arrangement of the coil current flow. Part of the current in the inner vertical field coils compensates the current in the connecting segments of the helical coils. The helical coils cause a toroidal translation of the magnetic field lines and assist in providing a seed paramagnetism. Similar coils sets previously proposed [2-4] did not explore the potential to seed paramagnetism, to improve confinement properties and to study MHD stability. A toroidal plasma current, nevertheless, must be driven in this device. The force-free current that it produces generates the toroidal (and poloidal) magnetic flux that guarantees the formation of flux surfaces and the confinement of the plasma. Furthermore, the current enhances the paramagnetic effect very strongly. A previous investigation has modelled the plasma current with fixed toroidal filaments and field line tracing studies have been applied to investigate the configurational properties of the system [1]. In this work, we apply the free boundary version of the three dimensional (3D) VMEC equilibrium code [5] using a distributed toroidal plasma current to obtain MHD equilibria that model the device. The local stability modules of the TERPSICHORE code [6] are applied to determine the Mercier criterion and the ideal ballooning stability characteristics of the equilibria. The global stability modules of this code are used to determine the stability with respect to internal and external kink modes.

2. MHD EQUILIBRIUM AND STABILITY

The parameters that have been investigated correspond to a current of $300kA$ in the helical coils ($75kA$ per filament), while the upper VF coil carries $-150kA$, the lower VF coil carries $+150kA$ and the outer VF coils have $-20kA$. The plasma current is varied from $-50kA$ to $-550kA$ with a peaked profile. The pressure, inverse rotational transform and differential volume profiles for a case with $-200kA$ and volume averaged $\beta = 2\mu_0 \int d^3xp / \int d^3xB^2 = 5.2\%$ is shown in Fig. 1b. The pressure profile is prescribed as $p(s) = p(0)[250(1-s^2)^2 + 5(1-s)]/255$ and the toroidal current profile is prescribed as $2\pi J'(s) = 0.5\pi J'(0)[3(1-s)^5 + (1-s^5)^2]$, where the symbol $'$ indicates a derivative with respect to s, where $0 \leq s \leq 1$ constitutes the radial variable proportional to the toroidal magnetic flux (plasma volume enclosed). The total toroidal plasma current is $2\pi J(1)$. The mod-B distribution on the cross sections at the beginning of the period and at half period are displayed in Fig. 2. The magnetic field has a maximum value of $1/3T$ at the magnetic axis and is much smaller towards the edge of the plasma. In the central region of the plasma, the mod-B contours align closely with the flux surfaces. They diverge towards the plasma boundary. The equilibrium state thus is nearly isodynamic [7]. In stellarator configurations, the curvature of the magnetic axis precludes the strict existence of isodynamicity. In our case, the plasma current induces a strong paramagnetic effect which produces the isodynamic conditions near the axis. However, this condition does not hold close to the plasma edge. Consequently, the configuration can be more closely associated with quasi-isodynamic [8] or pseudosymmetric [9] systems. The strong paramagnetism in the bulk of the plasma also produces a magnetic hill. This is not particularly favourable for MHD stability. The ballooning modes are stable and the Mercier modes are only unstable very locally near mode rational surfaces at $\beta \sim 5\%$ as shown in Fig. 3a. The Mercier criterion is marginally stable at midvolume and is more restrictive than localised ballooning modes. A further increase in β could be realised because there is room to increase the pressure gradient in the outer 1/3 fraction of the plasma volume and still remain stable to local modes. The large global magnetic shear generated with peaked current profiles constitutes an important stabilising mechanism for local MHD modes for $\beta < 6\%$. External $m/n = 1/1$ and internal $m/n = 1/3$ limit the toroidal plasma current to about -60 to $-70kA$. It must be noted that this limit is extrapolated from unstable configurations with higher current and that we have been unable to converge an equilibrium state when the current is smaller than $-90kA$. This could possibly indicate an equilibrium limit at low toroidal current, but has yet to be confirmed because we have calculated equilibria with broader current profiles at $-50kA$ and lower β. The configuration is clearly three dimensional for the parameters we have chosen. For the broader current profile cases we have investigated, the main effect of reducing the toroidal current to $-50kA$ (keeping the vertical field fixed) is to shift the plasma inwards away from the helical coils. The helical modulation becomes very weak and the system becomes practically axisymmetric. This configuration retains its strong paramagnetic character with the mod-B contours closely aligned with the flux surfaces near the central region. The plasma volume and cross section become smaller and the rotational transform increases.



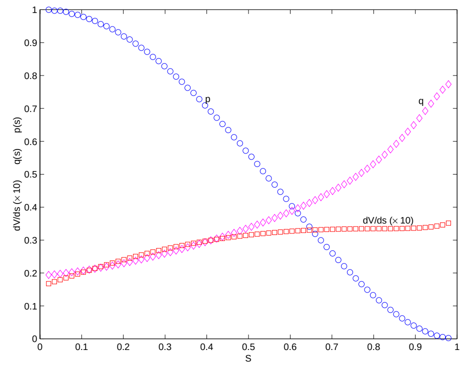
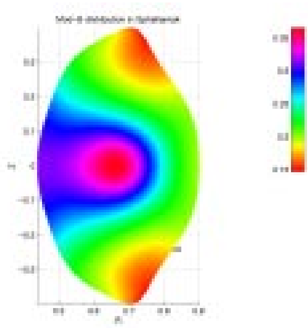


Fig. 1a. (left) The coil system of the Sphellamak configuration. There are 10 helical coils, an inner pair of vertical coils and an outer pair of vertical coils. Fig. 1b. (right) The differential volume ($\times 10$), normalised pressure and inverse rotational transform q profiles for a case with $-200kA$ toroidal current and $\beta = 5.24\%$.



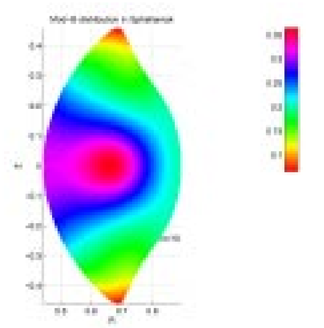
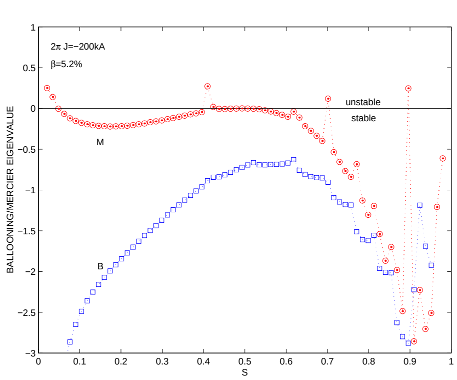


Fig. 2. The mod-B distribution in the Sphellamak at the beginning of the period (left) and at half period (right) for a case with $-200kA$ toroidal current and $\beta = 5.24\%$.



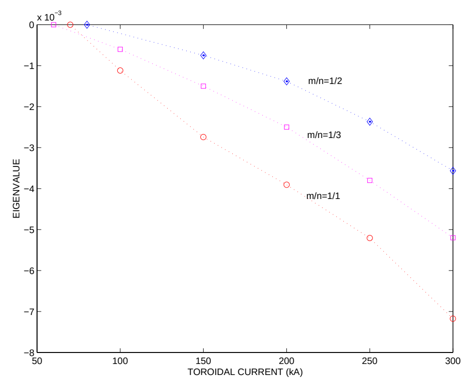


Fig. 3a. (left) The Mercier criterion (circles) and the ballooning eigenvalue (squares) profiles for a case with $-200kA$ peaked toroidal current and $\beta = 5.24\%$. Fig. 3b. (right) The eigenvalues of global modes dominated by the $m/n = 1/1$ (circles), the $m/n = 1/2$ (diamonds) and the $m/n = 1/3$ (squares) components as a function of the toroidal current for a sequence of Sphellamak equilibria with peaked current profiles and $\beta \sim 5\%$. The marginal points have been obtained by extrapolation. Negative eigenvalues indicate stable (unstable) conditions for local (global) MHD modes with the normalisation we have adopted.

The structure of the magnetic field implies that particles can be trapped only towards the plasma edge which localises any bootstrap current drive to that region. To model a bootstrap current, we prescribe a hollow current profile. The configuration under these conditions becomes quasiaxisymmetric. It is stable to Mercier and ballooning modes at $\beta \sim 10\%$ when the pressure profile is modified to have very weak gradients in the regions of vanishing global magnetic shear. However, it requires a tightly fitting conducting wall to stabilise external $m/n = 1/1$ kink modes with a toroidal current of $-400kA$. We have also considered a case with a mildly hollow current profile where we have changed the direction of the current in the helical coils so that the contribution of these coils to the rotational transform is opposite that of the plasma current. With a toroidal current of $-150kA$ and a tailored pressure profile to guarantee local MHD mode stability at $\beta \sim 5\%$, a close fitting conducting wall is also required to satisfy stability. This case is quasiaxisymmetric.

3. DISCUSSION AND CONCLUSIONS

The Sphellamak concept that relies on the toroidal plasma current to generate the toroidal magnetic field displays an extremely strong paramagnetic effect without requiring dynamo action. This results in a system that is nearly isodynamic, at least near the centre of the plasma. The resulting transport properties could approach classical levels making it a potentially very attractive system. A large fraction of the confining magnetic fields are produced from the force-free currents rather from external coils. Consequently, the values of β we have reported are significantly larger with other more conventional definitions of this parameter. If we replace the volume averaged magnetic energy density in the definition we adopt for β with the magnetic energy density from the vacuum fields only at the centre of last close flux surface, the value of β would exceed 500%. Global kink modes limit the maximum toroidal current that can be achieved in these configurations. A close fitting conducting wall is required with hollow toroidal currents that model the bootstrap effect. With peaked toroidal current, marginal stability with respect to kink modes with a conducting wall far from the plasma is satisfied for values of current ($-60kA$) where the computation of equilibria with the VMEC code has had difficulty to yield a converged solution so far.

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