Stabilizing Windings for the Tilting and Shifting
Modes in an Inductively Formed Spheromak

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ABSTRACT

It is shown that a set of 4 passive conducting coils, each with the figure 8 topology, will stabilize a spheromak to the rigid body toroidal mode number $n = 1$ tilting and shifting modes. The inclusion of these coils does not interfere with the inductive formation process.

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It has been demonstrated both theoretically^{1,2} and experimentally³ that it is possible to form a spheromak plasma in a quasi-static axisymmetric manner by inductively transferring both toroidal and poloidal currents from a flux core into the surrounding plasma. Once formed and separated from the rigid flux core, however, it is known that in the absence of nearby conductors⁴ or line tying effects,⁵ the plasma is unstable to a toroidal mode number $n = 1$ mode with a tilt and/or a shift polarity. This nearly rigid mode arises from the tendency of the plasma to tilt so as to align its magnetic moment with the externally imposed equilibrium field or to shift horizontally into a region of weaker magnetic field strength.

A systematic numerical stability study⁴ of this class of modes has shown that a spheromak plasma of circular cross section ($b/a > 1$) and with aspect ratio $R/a = 2$ can be completely stabilized by a pair of horizontal conducting plates located within half a minor radius of the plasma edge. However, it is not possible for these horizontal stabilizing plates to exist in an inductively formed device since the same conductors that inhibit the instability would effectively shield the plasma from the flux core, thus short-circuiting the inductive formation process.

The solution to this dilemma is illustrated in Fig. 1 where we present the figure 8 stabilizing windings. There are 4 independent figure 8 coils, two on the top oriented at right angles to one another, and two on the bottom. These passive coils should allow for the formation of $n = 1$ eddy currents⁴ which act to stabilize the plasma against tilt/shift modes, but have no inductive coupling with the axisymmetric flux core and thus will not interfere with the formation process.

To make quantitative estimates of the effective stabilization of these coils, we take a simple model in which the spheromak plasma is represented

by a rigid loop of radius r_0 carrying a current I_p . Let $B_z(r)$ be the external field required for equilibrium, with index $n_1 = (-r_0/B_z) \partial B_z / \partial r|_{r_0}$. When displaced to the side a distance d or tilted at an angle θ , the current loop interacting with the equilibrium field gradients will experience a force $(\partial F / \partial d)_e = n_1 I_p B_z(r_0)$ and a torque $(\partial W / \partial \theta)_e = \pi r_0^2 I_p B_z(r_0) (1 - n_1)$.

If the passive stabilization coils are in place, they will provide a restoring force $(\partial F / \partial d)_c = I_p^2 (\partial L_{cp} / \partial d)^2 / L_c$ and a restoring torque $(\partial W / \partial \theta)_c = I_p^2 (\partial L_{cp} / \partial \theta)^2 / L_c$. Here L_c is the effective self-inductance of the figure 8 coil system and L_{cp} is the mutual inductance between the plasma ring and the coils. The geometrical terms $(\partial L_{cp} / \partial d)^2 / L_c$ and $(\partial L_{cp} / \partial \theta)^2 / L_c$ are given in Tables I and II as functions of the vertical separation of the coils from the midplane, Z , and the radius of one loop of the figure 8, a . These were computed for coils with a 2 cm radius in which the figure 8 geometry is made by joining two tangent circular coils. If the stabilizing forces of the coils are greater in magnitude than the destabilizing forces due to the field gradients, the system will be stable to all rigid motions.

Thus, for example, a plasma ring centered at $r_0 = 0.4$ m with current $I_p = 350$ kA in an external field of strength $B_z(r_0) = 0.15$ tesla with index $n_1 = 0.9$ will have destabilizing forces due to the equilibrium fields of $(F/d)_e = 1.48 \times 10^5$ newtons/meter and $(W/\theta)_e = 2.64 \times 10^{11}$ newton-meters/radian. This will be stable to both the tilt and the shift mode by including a set of figure 8 coils with $Z = 0.2$ meters and $a = 0.3$ meters. This passively stabilized system would be expected to go unstable on the time scale $\tau_R \sim L_c/R$ where R is the resistance of the coils. An active feedback system⁶ would be necessary to obtain stabilization over a longer period.

ACKNOWLEDGMENTS

We thank Drs. H. P. Furth, M. Yamada, M. S. Chance, M. Okabayashi, J. Sinnis, G. V. Sheffield, and D. A. Monticello for their encouragement.

This work was supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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		a			
		0.2	0.3	0.4	
		0.4	6.8	23.4	30
z	0.3	17	64	72	$\times 10^{-8}$
	0.2	352	176	168	
	0.1	29.2	530	362	

TABLE I: Values of the geometrical parameter $(\partial L_{CP}/\partial d)^2/L_C$ for a 2 cm radius conductor.

		a			
		0.2	0.3	0.4	0.5
		0.3	1.5	0.56	0.014
z	0.2	9.1	3.2	0.046	0.22
	0.1	64	13	0.90	0.002

TABLE II: Values of the geometrical parameter $(\partial L_{CP}/\partial \theta)^2/L_C$ for a 2 cm radius conductor.

81T0118

Fig. 1 Four independent figure 8 coils, 2 on top and 2 on the bottom, will stabilize the $n = 1$ modes but allow the $n = 0$ formation process to occur.