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EXPERIMENTAL CONTROL OF THE SPHEROMAK TILTING INSTABILITY

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ABSTRACT

The magnetohydrodynamic (MHD) tilting instability of the spheromak configuration has been experimentally investigated by recording the time evolution of the magnetic field configuration with small magnetic probes. Passive coil systems such as the figure eight and saddle coils have been proven experimentally to be effective against this instability.

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In this paper, we report an experimental identification of the tilting mode of the spheromak plasma and the verification of the effectiveness of several passive stabilizing coil systems against this instability.

Since several different formation techniques have been demonstrated,¹⁻³ the viability of the spheromak as a fusion reactor concept now depends strongly on our ability to control its gross MHD instabilities. These have recently been the subject of intensive theoretical⁴⁻⁶ and experimental^{2,7} investigation. Theoretically, the most dangerous of these instabilities is a nearly rigid, toroidal mode number $n=1$, ideal MHD mode in which the spheromak tilts to align its magnetic moment with the externally applied magnetic field, and/or shifts horizontally into a region of weaker magnetic field strength.

The S-1 inductive formation technique^{3,8,9} is characterized by its slow (quasistatic) time scale and by its absence of the passage of large plasma currents through electrodes. This slow inductive formation scheme was first demonstrated with the Proto S-1/A device,³ which is now being used along with the newer Proto S-1/C device to study the gross MHD stability properties of the spheromak configuration.

Proto S-1/A consists of a cylindrical stainless steel vacuum vessel with a height of 75 cm and a diameter of 60 cm. External magnetic field coils produce an equilibrium magnetic field of adjustable strength $B_z(r_0)$ and field curvature index $n_1 \equiv (-r_0/B_z) \partial B_z / \partial r|_{r_0}$. Inside the vessel is a toroidal flux core of 15-cm major radius and 3-cm minor radius which contains the poloidal-flux (PF) and toroidal-flux (TF) coils. Proto S-1/C has a flux core with a 30-cm major radius, 6-cm minor radius, and an ellipsoidal vacuum vessel with a height of 96 cm and a diameter of 150 cm.

Magnetic field information is provided by probe arrays composed of five sets of orthogonal coils (B_r , B_θ , B_z) spaced 2 cm apart radially in Proto S-

1/A, and ≈ 5 cm apart in .roto S-1/C. These probes may be rotated toroidally and translated axially, providing access to the entire spheromak region. Plasma reproducibility is generally very good ($\frac{\Delta B}{B} \lesssim 0.05$), therefore multi-shot scans along z may be performed at a number of toroidal angles to give a detailed global time evolution of the magnetic field configuration.

For a field index near zero, a tilting instability occurs when the stabilizing coils are absent. The tilting is particularly reproducible in Proto S-1/A, apparently due to the magnetic perturbation of the current leads to the core, and proceeds on an axis defined by these leads.

Complete field information in a plane perpendicular to the tilt axis allows the experimental determination of the growth rate of the tilting instability:

$$\gamma_t = \frac{1}{\theta_t} \frac{d\theta_t}{dt}.$$

Theoretical growth rates of the unstable $n=1$ modes in these devices can be estimated by approximating the spheromak plasma by a rigid toroidal loop of mass m_p , major radius r_0 , and minor radius a , carrying a toroidal current I_t . If there are N discrete conductors in proximity to the plasma, each with self inductance L_n and mutual inductance with the plasma M_{np} , then the growth rates for horizontal shifting in direction x and tilting through an angle θ are given (for $r_0 \gg a$, $\theta \ll 1$) by:

$$m_p \gamma_s^2 = \pi I_t B_z(r_0) n_1(r_0) - I_t^2 \sum_{n=1}^N (\partial M_{np} / \partial x)^2 / L_n, \quad (1a)$$

$$\frac{1}{2} m_p r_o^2 \dot{\gamma}^2 = n r_o^2 I_t B_z(r_o) (1 - n_1(r_o)) - I_t^2 \sum_{n=1}^N (\partial M_{np} / \partial \theta)^2 / L_n. \quad (1b)$$

To suppress these two instabilities, a stabilizing conductor should be oriented to maximize its inductive coupling with the shifting and tilting motions of the plasma, $(\partial M_{np} / \partial x)^2$ and $(\partial M_{np} / \partial \theta)^2$. However, since the plasma is inductively formed, the mutual inductance between the stabilizing conductor and the flux core must be kept to a minimum to avoid short-circuiting the toroidal plasma current during the formation phase.

Figure 1 presents the theoretical behavior of the normalized growth rate based on Eq. (1b) without discrete conductor effects, and the experimental results obtained. The deviation of the experimental data from theory is attributed to stabilizing effects of eddy currents at the flux core surface and line-tying effects of poloidal field lines which go around and/or intersect the flux core.

Two types of stabilizing coils have been tried in the experiments. The design of the figure eight coils [Fig. 2(a)] is based on the computed pattern^{6,10} of eddy currents that would appear in a nearby conducting wall when an $n=1$ displacement of the spheromak occurs. Saddle coils^{11,12} [Fig. 2(b)] are effective against tilting, while figure eight coils^{10,12} are effective against tilting and shifting.

To stabilize the tilting instability, passive figure eight coils have been constructed from 3/16 in. copper rod and mounted as shown in Fig. 2(a). Two independent sets of coils are located at 90° to one another, both on top and bottom, to stabilize tilt or shift motions in the two orthogonal directions. It is readily seen that the "twist" in the coils forces the flux

contribution from the axisymmetric flux core to cancel, thereby assuring that there is no inductive coupling to the PF circuit.

Figure 3 shows, in the left column, the time evolution of the toroidal field configuration (B_t contour) in the R-Z plane in Proto S-1/A for a tilting instability ($\gamma_t = 0.28/\mu\text{sec}$ for $n_1 = -0.1$). In the right column is the same operational mode after the addition of figure eight coils with the inner edges 6 cm from the midplane of the core. All machine parameters, i.e., core currents, equilibrium vertical field, and gas fill pressure are identical for the two cases. It is apparent that the coils have had a stabilizing effect on the tilting.

To verify further the stabilizing effects of the figure eight coils, we have repeated the field measurements with only one coil on top, and an identical coil on the underside. As expected, the spheromak then has a tendency to tilt in a direction 90° to the coil loops where the coils produce no stabilizing reaction.

Figure 4(a) shows the results of decreasing the distance from the inner edges of the figure eight coils to the midplane of the plasma in Proto S-1/A. As the coils are moved closer to the midplane, the stable period (τ_s) during which θ_t is very small increases rapidly. With the coils at the 12-cm position, τ_s is $\approx 2\frac{1}{2}$ μsec out of a total plasma lifetime of ≈ 25 μsec . The total plasma lifetime is limited largely by radiative energy loss and resistive decay.

It is observed that even with the stabilizing coils in an optimized position, an unstable mode still develops about $10\text{--}20$ μsec later than the no-coil operation. This is believed to be caused by the decay of the plasma to a point where the present (optimized for $r_0 = 6$ cm) coils are no longer effective. It might also be explained as the onset of a higher order mode

unaffected by the coils, but there is no direct experimental evidence of this.

Saddle coils have also been constructed and installed as shown in Fig. 2(b). Figure 4(b) shows the effects of the saddle coils on a tilt mode in Proto S-1/A originally having $\gamma_t \approx 0.17$ for $n_1 \approx -0.05$. It is clear that the coils have suppressed the instability.

The effectiveness of the figure eight and saddle coils has been verified in both Proto S-1/A and Proto S-1/C. In Proto S-1/A, the spheromak plasma has been kept stable for $\approx 21 \mu\text{sec}$ ($\approx 25 \mu\text{sec}$ total lifetime) by insertion of the figure eight or saddle coils, while in Proto S-1/C the plasma has been kept stable for $40 \pm 60 \mu\text{sec}$.

Recently, a shift instability has also been identified in Proto S-1/C when the field index is positive ($n_1 \approx 0.2$). The growth rate of the mode is observed to be about the same as that of tilt mode:

$$\left(\gamma_s = \frac{1}{R} \frac{\partial R}{\partial t} = \gamma_t \right).$$

The figure eight coils have been proven to be effective against the shifting instability by H. Bruhns et al.¹³

In conclusion, the gross MHD behavior of spheromak plasmas in the Proto S-1 devices has been studied, and the tilting instability identified. Passive stabilization coils of the figure eight and saddle type have proven to have a significant stabilizing effect on the tilting mode while not interfering with the inductive formation process. This demonstration of the stabilization of gross instabilities with loosely fitting passive coils, as opposed to closely fitting conducting shells, should considerably enhance the attractiveness of

the spheromak concept for a fusion reactor, since it would greatly alleviate first wall problems.

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FIGURE CAPTIONS

FIG. 1 Comparison of the experimental growth rates normalized by $\gamma_c(m_p[1+(5/4)(a/r_0)^2])^{1/2}(2\pi I_c B_z)^{-1/2}$, with respect to the field index n_1 , and the theoretical prediction. The experimental range of index available is limited by plasma formation requirements.

FIG. 2 Two types of coils for stabilizing the $n=1$ MHD modes of the spheromak. Type (a), the figure eight coils, will stabilize tilt or shift motions, type (b) saddle coils are effective only against the tilting mode.

FIG. 3 Experimental verification of the effectiveness of the figure eight stabilizing coils in Proto S-1/A. The left side shows toroidal field contours as a function of time without figure eight coils, the right side with them. All other parameters are kept the same.

FIG. 4(a) Time evolution of θ_c for cases having the figure eight coils increasingly closer to the plasma midplane, $z=0$.

4(b) Time evolution of θ_c for a case with, and without the saddle coils.

Fig. 1

82 X 0777

(a)

(b)

Fig. 2

82 X0879

CONTOUR PLOT OF B_1 ON R-Z PLANE
STEP SIZE: 300 G

Fig. 3

Fig. 4a

Fig. 4b

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