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TITLE: EQUILIBRIUM AND STABILITY OF THE LOS ALAMOS SPHEROMAK

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EQUILIBRIUM AND STABILITY OF THE LOS ALAMOS SPHEROMAK*

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The open mesh flux conserver (MFC) on the Los Alamos spheromak (CTX) has been equipped with a large number of Rogowski loops measuring the current in the individual segments of the MFC, providing a complete picture of the surface current pattern induced by the equilibrium and oscillations of the confined plasma. Analysis of the data from these Rogowski loops reveals an interesting picture of the behavior of CTX.

During mixed mode operation, the CTX evolves through two distinct phases.[1] At the beginning of the shot the gun injects helicity into the MFC and drives current along the open field lines, which wrap around the outside of the plasma (see Fig. 1-a).[2] This causes the λ profile ($\lambda = j_{\parallel}/B$) to have a higher value at the edge than in the core. During this time the Rogowski loops show the presence of an $N = 1$ distortion in the plasma that rotates at the $E \times B$ drift velocity produced by the radial electric field in the gun.[3]

Later in the shot, the gun voltage is turned off and the plasma separates and resistively decays (see Fig. 1-b). The higher resistivity near the edge of the plasma causes the current to decay faster there, producing a λ profile that is lower at the edge than in the core. At this time the Rogowski loops show that the $N = 1$ oscillation has stopped and an $N = 2$ distortion appears in the plasma, rotating in the direction of the electron diamagnetic drift.[3] The $N = 2$ oscillation continues till the end of the shot.

This behavior can be explained by zero-beta ideal MHD stability theory.

An equilibrium for CTX can be calculated by solving the Grad-Shafranov equation, taking into account the discrete nature of the toroidal hoops in the MFC. For simplicity, the changing λ will be modeled with only one adjustable parameter to control the gradient:

$$\lambda(\psi) = \lambda_0\left(1 + \alpha\left|2(\psi/\psi_{max}) - 1\right|\right) \quad . \tag{1}$$

During a single shot α will take on first negative then positive values as the spheromak evolves from the sustained to the decaying phase. Figure 2 shows the minimum energy equilibrium ($\alpha = 0$) in the 140 cm MFC. The value of α can be inferred from tthe data by comparing the measured distribution of equilibrium toroidal currents in the MFC with Fig. 3, which shows how the calculated distribution changes with α. When $\alpha < 0$ and λ is higher at the edge of the plasma the current shifts inward toward the symmetry axis, and when $\alpha > 0$ it shifts outward.

Stability is determined by calculating the fastest growing mode of the zero-beta ideal MHD stability equation

$$\gamma^2 \underset{\sim}{A} + V_A^2(\underset{\sim}{j}-\lambda\underset{\sim}{B})_\perp = 0 \quad , \tag{2}$$

for an equilibrium having the same $\lambda(\psi)$ but in a solid cylindrical flux conserver with the same length and radius as the MFC. The square of the growth rate, normalized to the Alfvén transit time (τ_A = radius of MFC divided by v_A at the center of MFC) is plotted in Fig. 4 as a function of α for the N = 1 and N = 2 modes.

Near $\alpha = 0$ the plasma is stable as one would expect, since this is the minimum energy state. Deviation from the minimum energy state in either direction causes instability. An N = 1 internal kink is unstable when $\alpha \lesssim -0.5$ or when λ at the edge exceeds three times λ at the magnetic axis. An N = 2 internal kink is unstable when $\alpha > 0.3$ or λ at the edge becomes less than half λ at the magnetic axis.

It is instructive to look at the q profile shown in Fig. 5 as a function of ψ in the minimum energy state, and at the two marginal stability points. The N = 1 mode becomes unstable when q becomes greater than 1 throughout the plasma, and the N = 2 when it drops below 0.5. Since both unstable modes are nonresonant, they should saturate nonlinearly and a rotation caused by $E \times B$ or electron diamagnetic drifts will produce the oscillating signals observed in the experiment.

The oscillations in CTX are thus explained as rotating saturated kink modes that become unstable whenever $j_\parallel/B$ becomes sufficiently inhomogeneous. The N = 1 appears when an excess $j_\parallel/B$ at the edge raises q above 1, and the N = 2 appears when a deficit of $j_\parallel/B$ at the edge lowers q below 0.5.

References

1. H. W. Hoida, et al., "Mixed Mode Operation in CTX," this proceeding.
2. I. Henins, et al., "Ohmic Heating to 100 eV and Helicity Injection in CTX," this proceeding.
3. B. L. Wright, "Analysis of Surface Currents on the CTX Mesh Flux Conserver," this proceeding.

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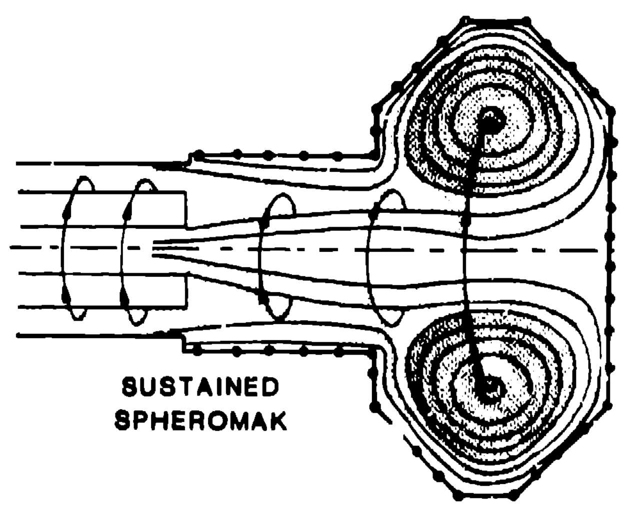

Fig. 1a

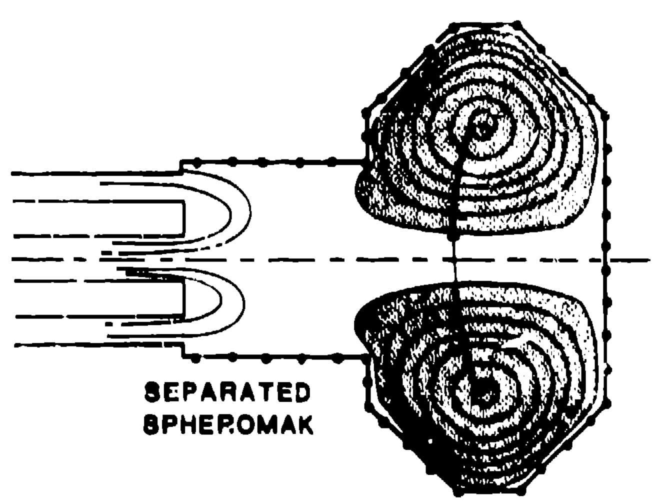

Fig. 1b

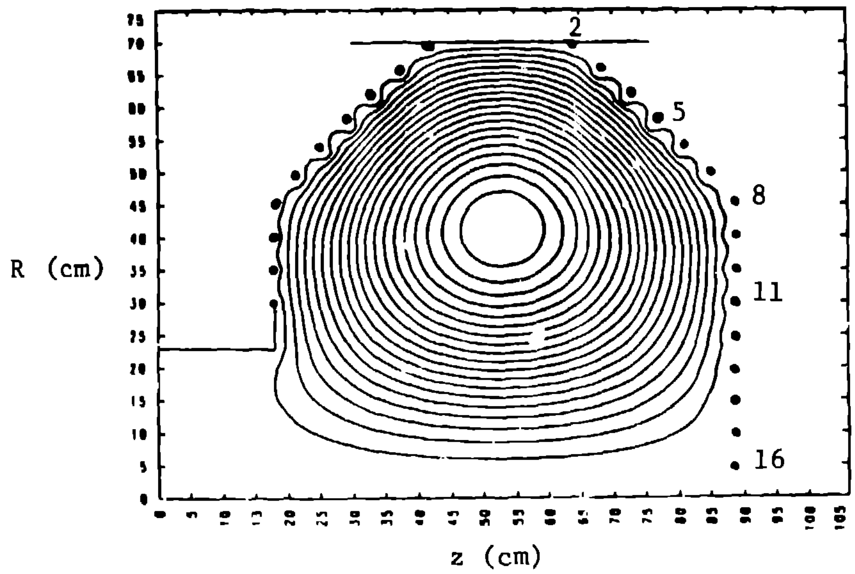

Fig. 2 - Equilibrium of CTX in the minimum energy state.

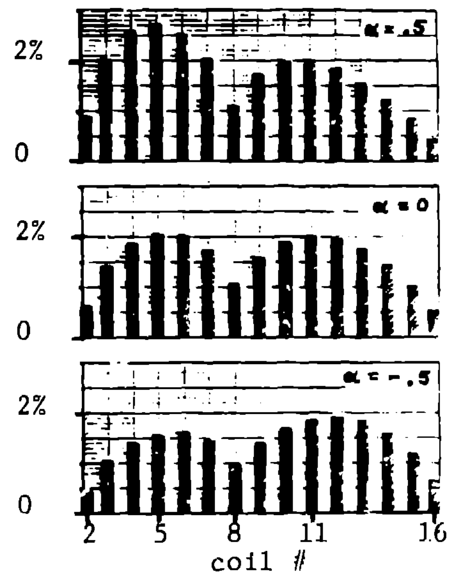

Fig. 3 - Hoop currents normalized to plasma current.

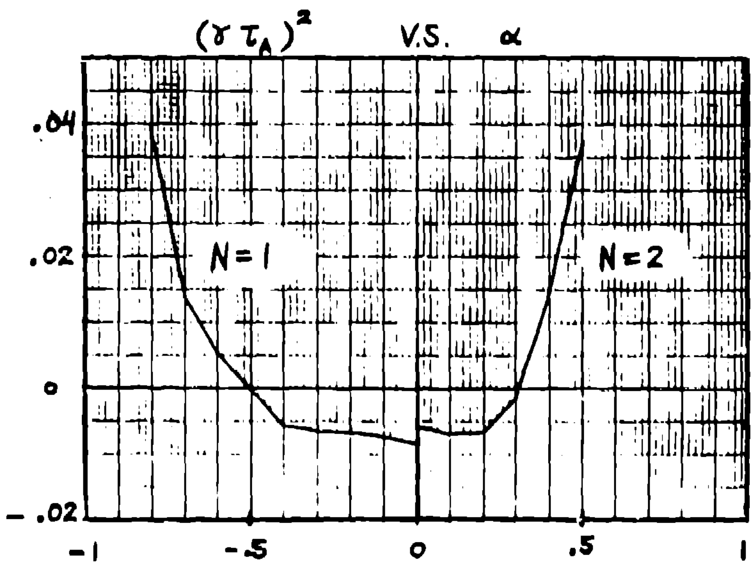

Fig. 4 - Growth rates of N = 1 and N = 2 internal kink modes as a function of α.

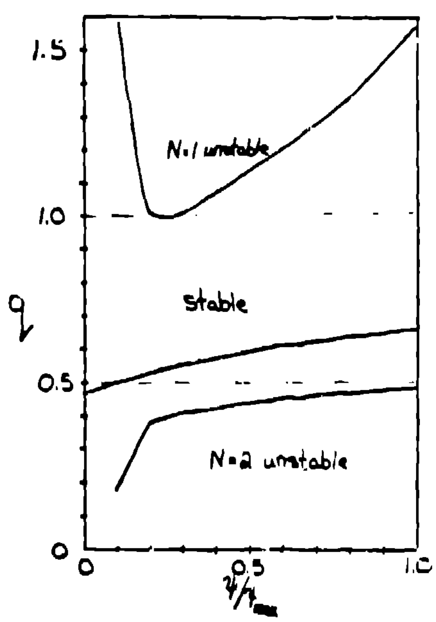

Fig. 5 - q profile at minimum energy and at the two marginal stability points.