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By

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ABSTRACT

The stability of spheromak equilibria with a flux core, or reversal coil, is studied by means of an ideal MHD code. Results depend critically upon whether the flux hole region (the current free area just inside the separatrix) is treated as perfectly conducting plasma or as vacuum. This indicates that the tilt and shift modes persist as resistive instabilities if they are stable in ideal MHD. Specifically, for nonoptimally shaped equilibria, the flux core must nearly touch the current channel if the flux hole is vacuum, whereas the core may be slightly outside the separatrix if the flux hole has conducting plasma. A larger margin exists for optimally shaped equilibria.

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Tilt and shift modes[1-4] are to date the most important global instabilities in spheromaks. Indeed, they have been observed in every experiment to date.[5-7] Previous work on these modes indicates that for long plasmas, with a small vertical field index (specifically $Z_s/R_s \gtrsim 0.6$, where Z_s is the half length of the separatrix enclosing the closed flux surface region and R_s is its radius; see Fig. 1), the tilt is the most unstable mode.[3,4] A mode crossing occurs near $Z_s/R_s = 0.6$ so that for shorter plasmas, with a larger field index, the shift mode has the larger growth rate.[3,4]

Previous studies have had spherical or cylindrical conducting walls. In all cases one or both modes are unstable with the walls far from the plasma, but are stabilized as the walls are moved in.[3,4]

Previous studies have also considered the open field line region to be plasma (and thus to be line-tied to the walls)[3] or vacuum.[3,4] All studies of these modes after the earliest had a so-called flux hole region just inside the separatrix where no current (poloidal or toroidal) flows. In some cases this region was treated as conducting plasma[3] and in others as vacuum,[4] but no systematic comparison between these two models has been performed.

In this paper we consider spheromak equilibria with a flux core (or field reversal coil) within the conducting walls as in the Princeton experiment S-1 and in the Maryland device MS currently being designed. The difference in terminology reflects the fact that the flux core in S-1 is responsible for inducing both poloidal and toroidal fields, whereas in MS the coil or coils will be responsible for poloidal fields only.

In the equilibrium code used, the boundary conditions on the poloidal flux ψ are $\psi(r,z)$ on the cylindrical walls, corresponding to bias coils providing a given field index (mirror ratio) and ψ = const on the surface of the flux core (reversal coil). The equilibria considered have

$rB_\phi = g(\psi) = \mu_o\ [(\psi/\psi_m - \psi_o/\psi_m)^2 + \varepsilon^2]^{1/2} - \varepsilon$, where r, ϕ, z is a cylindrical coordinate system with ϕ the toroidal angle, ψ_m is the flux at the O-point on the magnetic axis, ψ_o is the flux at the inner boundary of the flux hole, ε is a parameter determining the size of the region over which the current goes to zero, and μ_o determines the overall plasma size. These equilibria and their stability, without a flux core, have been studied in Ref. 3. For the present purposes we fixed ψ_o and ε to the values found to be optimal in Ref. 3 .

The stability code used here is the initial value ideal MHD code described in Ref. 3. Line tying was not included, i.e., the open field line area was considered to be vacuum. We do not move walls to find marginal stability, but rather vary ψ_c, the flux on the flux core. Decreasing ψ_c decreases the distance between the core and the separatrix and for $\psi_c < 0$ wraps more of the flux in the closed flux surface region around the core. Since the core is of finite size, to some extent it can carry the same types of eddy currents as can a cylindrical or spherical wall.

We treat the flux hole region as either perfectly conducting plasma or as vacuum in order to compare the results. As is well known, a closed flux surface region outside a current carrying plasma provides a stabilizing influence in MHD if it contains perfectly conducting fluid, as compared to the case when the region has vacuum, and if a mode rational surface m = nq (m is the poloidal mode number, n the toroidal mode number, and q the safety factor) exists in the region. Tilt and shift modes are basically m = 1 modes, but their m = 0 components, present because of toroidal effects, satisfy m = nq throughout the region, where q = 0. On this basis we should expect plasma in the flux hole region to have a stabilizing effect.

The stability results we present are the growth rate of the most unstable mode normalized by a nominal Alfvén time $\gamma a/v_A$, where a is the wall radius.

The density is assumed to be uniform throughout the plasma. This is plotted against ψ_c, the flux at the flux core (reversal coil), normalized to a flux $\psi = B_o a^2/2$ based on a nominal field B_o. [In this normalization ψ_m, the value at the magnetic axis, is generally -0.3, $\psi(a,o) \simeq 0.3$, and $\psi(a,L)$, where L is the length of the cylindrical can, is considerably larger due to field index.]

The first set of equilibria has a fairly large field index that produces a nearly optimally shaped plasma ($Z_S/R_S \simeq 0.6$) when the flux core is absent. For the model with plasma in the flux hole, the growth rate shown in Fig. 2 as a function of ψ_c decreases as $\psi_c \to 0$, with a plateau near $\psi_c = 0.10$. The eigenfunctions are about equally tilt and shiftlike in this region indicating that the plateau is due to proximity to the mode crossing point. Below $\psi_c = 0.10$, γ decreases fairly sharply again and marginal stability occurs at $\psi_c = 0.025$. The plasma is very oblate at this point and the eigenfunction is almost a pure shift mode. Flux surfaces for an equilibrium near the marginal point are shown in Fig. 1.

In Fig. 2 we also show the growth rate as a function of ψ_c for the high index equilibria when the flux hole region is considered to be vacuum. Here the growth rates are much larger. There is again a plateau due to mode crossing near $\psi_c = 0.05$ and marginal stability at $\psi_c = -0.06$. The edge of the plasma for this case is at $\psi_c = -0.062$ so that, within computational error, the flux core needs to touch the edge of the plasma to stabilize the mode. At marginal stability the plasma is very oblate and the eigenfunction is very shiftlike.

Next, we show a sequence of equilibria with a smaller field index in order to be nearer the optimum shape at marginal stability. First consider the cases where the flux hole is filled with plasma. As seen in Fig. 3, γ here is much larger in the range $0.1 < \psi_c < 0.2$, relative to the cases of

Fig. 2, and examination shows an extremely tiltlike eigenfunction due to elongation. For $0.05 < \psi_c < 0.1$, the eigenfunction is a mixture of tilt and shift, i.e., near the mode crossing; the growth rate decreases sharply showing marginal stability at $\psi_c = 0.05$.

The low field index case with vacuum in the flux hole is also shown in Fig. 3. Again, growth rates are much larger compared with the case of plasma in the flux hole region. There is a slight plateau in growth rate above $\psi_c = 0.10$ and a sharp drop for $0.05 < \psi_c < 0.10$, where the mode is becoming more shiftlike as ψ_c decreases. Marginal stability occurs at $\psi_c = 0.05$ and the edge of the plasma is at $\psi_c = -0.066$ in this case. Marginal stability in this case has the flux core slightly more removed from the plasma than in the high field index case, due to the plasma being slightly longer. Flux surfaces for a low field index equilibrium near marginal stability are shown in Fig. 4.

These results show further evidence of the fact that for nonoptimally shaped plasmas (generally outside the range $Z_s/R_s = 0.6 \pm 10\%$), a metal wall must nearly touch the plasma at some point to stabilize tilt or shift modes. In our cases this means that the flux core must nearly touch the separatrix whenever the flux hole region is plasma (although the spacing is not so small in the low field index case because the plasma is nearly optimally shaped at marginal stability). When the flux hole region is considered to be vacuum, the core must nearly touch the current carrying plasma. The advantage in having a large amount of flux from the closed field line region around the core, namely having the conducting core material near the plasma, is nearly offset by the fact that this mode of operation produces very oblate plasmas subject to shift modes.

We have shown that there is a substantial difference between the results obtained by treating the flux hole region as a conducting plasma (without current) on the one hand and as a vacuum on the other. In the typical experiment, the flux hole region contains plasma which is conducting but cooler, and therefore more resistive than the core of the plasma. Therefore, our results show that tilt and shift modes, when they are observed in plasmas with a flux core near or within the separatrix, are resistive instabilities. We have bracketed these results with two models, treating the flux hole region as perfectly conducting and as nonconducting, respectively. However, to compute the actual growth rate, whenever the former model predicts stability and the latter model predicts instability, a code with finite resistivity is required.

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FIGURE CAPTIONS

Fig. 1 Flux surfaces for a high field index spheromak equilibrium with flux core (reversal coil) near the separatrix, $\psi_c = 0.05$. This equilibrium is nearly marginally stable if the flux hole is filled with plasma.

Fig. 2 Normalized growth rate γ as a function of ψ_c the flux at the flux core, for the high index class of equilibria with plasma in the flux hole region (bottom curve) and with vacuum in the flux hole region (top curve).

Fig. 3 Normalized growth rate γ as a function of ψ_c for the low index case with plasma in the flux hole region (bottom curve) and with vacuum in the flux hole region (top curve).

Fig. 4 Flux surfaces for a low field index spheromak with flux core (reversal coil) inside the separatrix $\psi_c = -0.025$. This equilibrium is nearly marginally stable with vacuum in the flux hole region.

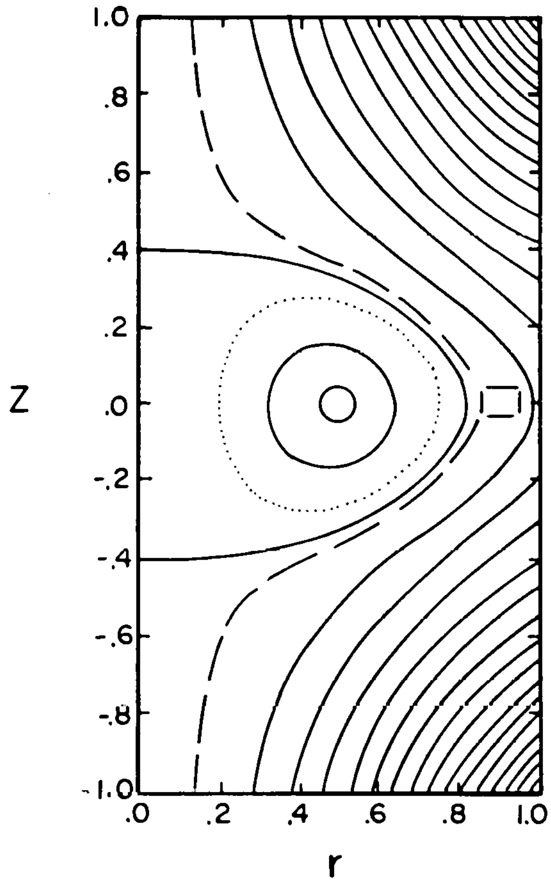
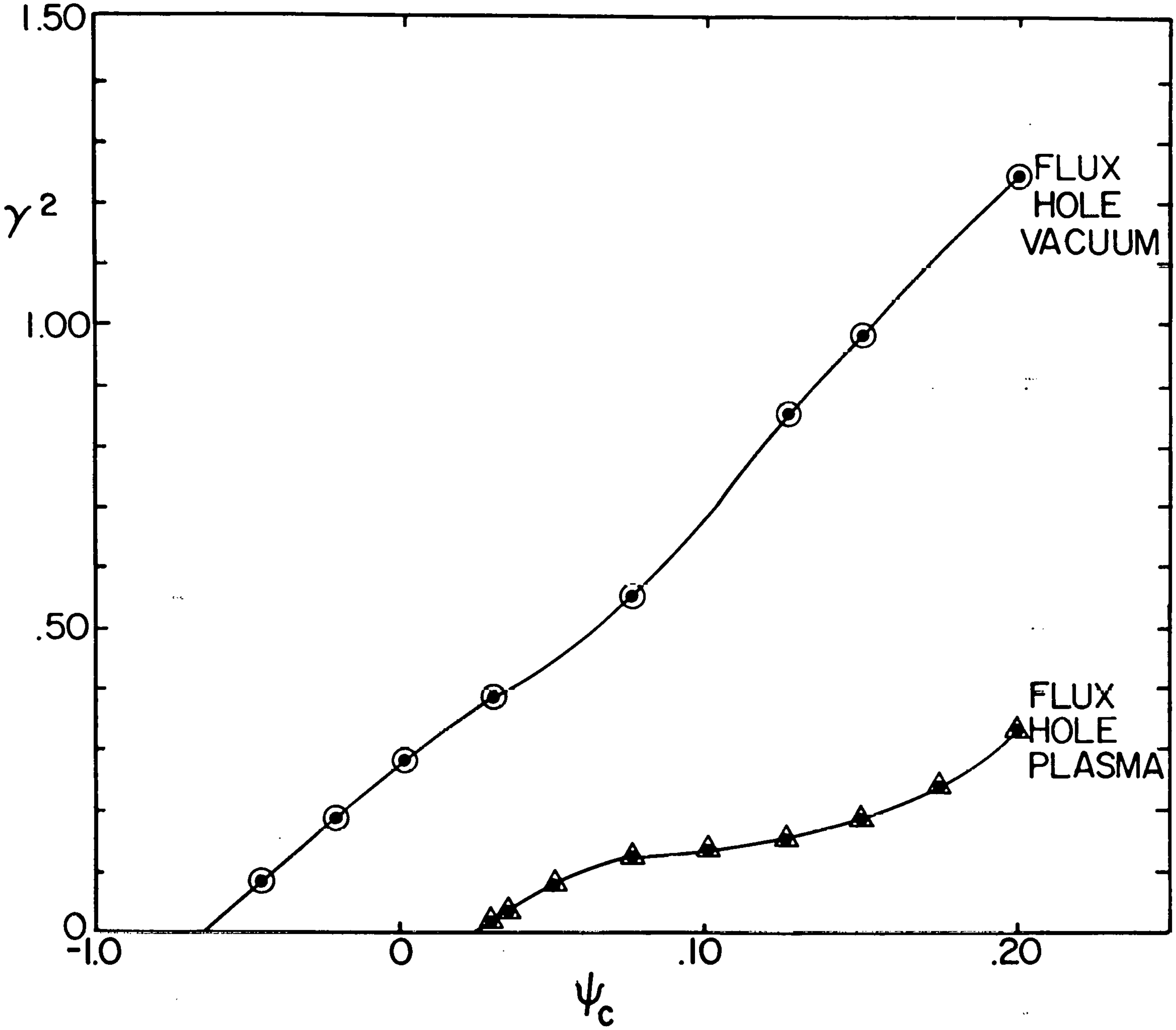


Figure 1


1.50
1.00
.50
0
γ^2
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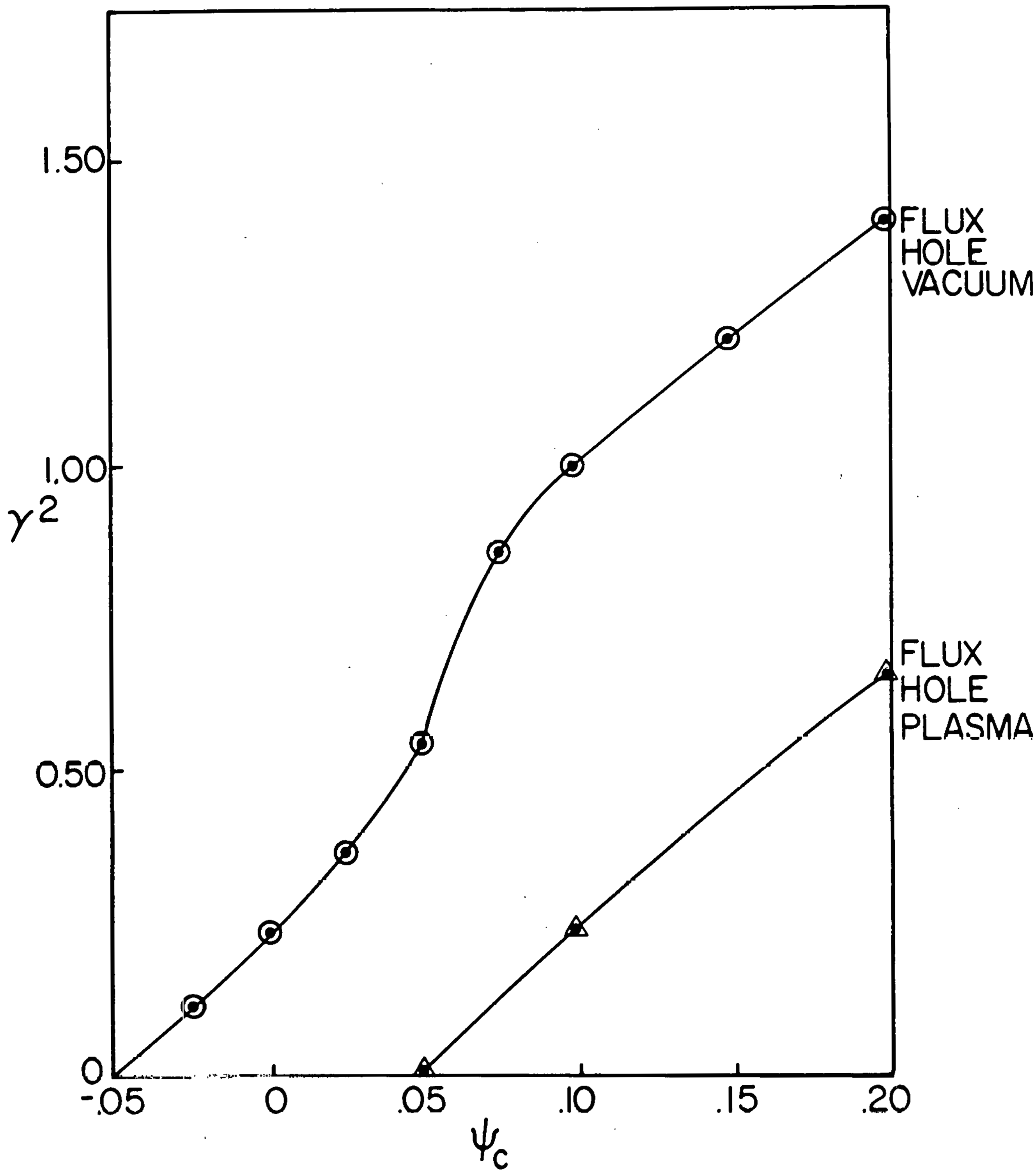
0
.10
.20
ψ_c
FLUX
HOLE
VACUUM
FLUX
HOLE
PLASMA

Figure 2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FLUX HOLE PLASMA

Figure 3

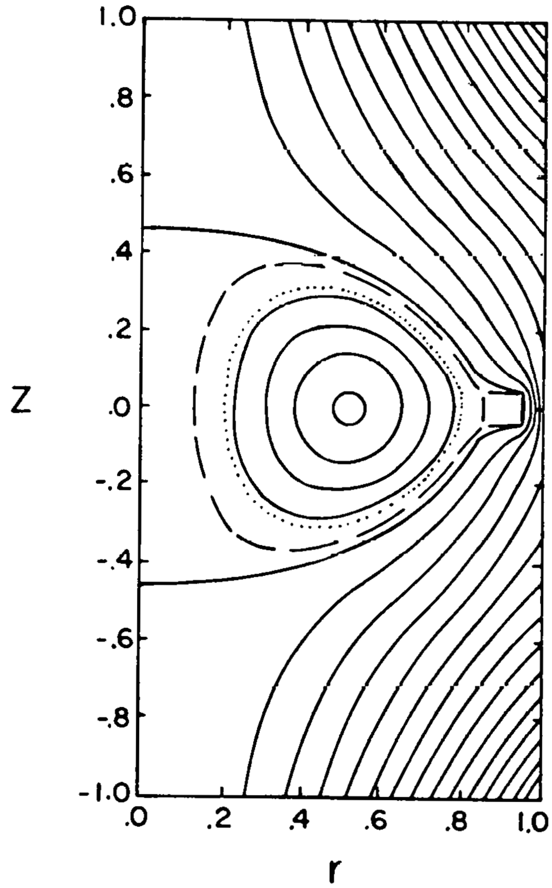

Figure 4

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