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RELAXATION OF SPHEROMAK PLASMAS TOWARD A MINIMUM-ENERGY STATE THROUGH GLOBAL MAGNETIC FLUCTUATIONS

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ABSTRACT

Globally coherent modes which are observed during formation in the S-1 Spheromak plasma are shown to be important for flux conversion and plasma relaxation toward a minimum-energy state. A significant finding is the temporal progression through the $n = 5, 4, 3, 2; m = 1$ mode sequence as q rises through rational fractions m/n, where n and m are defined by the functional dependence $e^{i(n\phi + m\theta)}$ of the fluctuations on toroidal angle ϕ and poloidal angle θ. Resistive MHD analysis predicts the observed modes and the sequence of occurrence.

A spheromak[1] is a toroidal magnetic confinement configuration for plasmas. The toroidal field in the plasma is sustained entirely by poloidal plasma currents, eliminating the need to link the plasma topologically. An important observation in spheromak experiments[2] is the tendency for plasmas to relax toward the force-free, minimum-energy Taylor[3] state. In recent S-1 Spheromak experiments,[4,5] magnetic flux conversion between the poloidal and toroidal fluxes of the plasma was observed during, and after, formation. This Letter presents the experimental identification, and origin, of magnetic fluctuations which play a significant role in the conversion process.

Flux conversion between poloidal and toroidal fields has become a topic of strong interest in the general plasma physics community since it has applications also to reversed-field pinches (RFPs) and tokamaks. This phenomenon is important not only for relaxation of these plasmas to a stable, minimum-energy state, but also for sustainment.[6,7]

The plasma formation in the S-1 spheromak device is based on an inductive transfer of toroidal and poloidal magnetic flux from a toroidal "flux core" to the plasma[5] (Fig. 1). Currents from the toroidal and poloidal field power supplies (capacitor banks) are programmed to induce poloidal and toroidal plasma currents simultaneously so that the magnetic configuration can be guided toward the minimum-energy Taylor state.

Properly detailed programming of the formation process was found not to be essential since plasmas were observed[4,5] to adjust themselves during formation to a final equilibrium near the force-free, minimum-energy Taylor state. The ratio of the toroidal plasma current to toroidal magnetic flux in the plasma, I/Φ, assumed a constant value independent of initial conditions such as capacitor bank voltages. I/Φ is proportional to the pinch parameter θ

of RFP research through a simple geometric factor involving the plasma size. It was experimentally observed in S-1 that this I/Φ ratio was maintained for the duration of a discharge. If the plasma evolved after formation such that the I/Φ ratio deviated too far from an acceptable range, then relaxation oscillations, with associated $m = 0$ precursor oscillations, restored I/Φ to a range commensurate with that theoretically predicted on the basis of a force-free, minimum-energy state equilibrium. In an attempt to understand these phenomena further, a magnetic coil system external to the plasma was installed to look for mode structure of the magnetic fluctuations.

The S-1 device has been creating a plasma with a major radius of about 55 cm and a minor radius of about 30 cm. Toroidal plasma currents up to 350 kA are obtained. Peak plasma electron densities n_e range from 2×10^{13} to 1×10^{14} cm^{-3}; measured electron temperatures T_e range from 20 to 110 eV. Stability against rigid-body $n = 1$ modes is provided by a passive Figure-8 stabilization coil system.[5]

The n-mode diagnostic coil array consists of 16 pairs of magnetic pick-up coils distributed toroidally to measure major radius and toroidal components B_R and B_ϕ, respectively, inside the vacuum vessel at a major radius of 50 cm and an axial position of 60 cm (Fig. 1). The coils are located just outside of the Figure-8 coil system and the Figure-8 coil system is, in turn, outside the separatrix of the spheromak magnetic configuration. The coils are designed to measure magnetic field fluctuation levels of 1 G (~ 0.1%) in a typical frequency range of 5-10 kHz (Bandwidth = 80 kHz). The $\dot{B}$ data are digitally integrated to obtain $B(\phi,t)$ which is then resolved into toroidal n-modes by use of discrete Fourier transformation.

The $q(\Psi)$-profile is obtained from $q(\Psi)=\Delta\Phi/\Delta\Psi$, where $\Delta\Phi$ is the difference in toroidal flux between two nearby poloidal flux surfaces Ψ and $\Psi+\Delta\Psi$, and Ψ

and Φ are obtained from two-dimensional flux plots.[5] The experimentally obtained contours of constant poloidal flux toward the end of the formation phase wherein the spheromak configuration is not completely detached from the flux core are shown in Fig. 1.

Globally coherent fluctuations, hereafter called modes, are observed almost always during the formation phase (Fig. 2). The modes show a well-defined dependence $e^{i(n\phi+m\theta)}$ on toroidal angle ϕ and poloidal angle θ, with n typically in the range 1 to 5, and m = 1. B_R and B_ϕ data agree with respect to which modes are present and to their evolution, implying modes correspond to a helical deformation of the toroidal current column. Modes are often evident from the 16 channels of $\dot{B}$ data as disturbances periodic in ϕ with integer number of periods around the torus, and larger amplitude modes are sometimes seen on the integrated data, B.

The n = 0 component of the measured B_R fields, which is primarily comprised of the unperturbed axisymmetric poloidal field of the spheromak configuration, is on the order of 0.5 to 1.0 kG, comparable to the magnetic field inside the plasma. Peak amplitudes of the modes relative to the unperturbed field are typically below 5%, while amplitudes as high as 20% were observed. After formation, amplitudes are less than 1%.

The n = 1 mode is most often associated with a shift or tilt of the plasma and leads ultimately to the termination of the discharge for well-detached plasmas while higher n modes never cause termination. Modes always rotate in the electron diamagnetic drift direction (based on the poloidal magnetic field), same as the direction of propagation of magnetic field fluctuations observed in tokamaks. Rotation velocities range from 0.12 to 1.2 $\times 10^6$ cm/sec, approximately 1/10 the Alfvén velocity. Occasionally, two modes are present simultaneously with velocities differing by as much as a factor of three, suggesting rotation is not associated with a rigid-body rotation of the plasma. Also, the rotation velocity often slows with time, indicating a possible dependence of the rotation velocity on B, n_e, or T_e. Frequency of the magnetic field fluctuations due to the rotation ranges from 2 kHz to 10 kHz and above.

The poloidal mode number during the time period of strong magnetic mode activity is determined to be m = 1 from ultra-soft X-ray system measurements which show a dominant m = 1 structure. Theoretical analysis[8,9] predicts that the m = 1 modes are most unstable.

These modes are important for relaxation to a Taylor state. Time evolution of the inventory of poloidal and toroidal fluxes derived from flux plots shows that there is a sudden (relative to the formation time) and (sometimes large) exchange of fluxes during the period of strong mode activity midway through the formation leading to a quiescent equilibrium, after formation, near the Taylor state. In Fig. 3, the poloidal flux (a) captured by the spheromak drops precipitously during the same period that there is a large increase in the toroidal flux (b) in the plasma. Figure 3b shows the toroidal flux within a closed poloidal flux surface defined by a constant poloidal flux distance $|\Psi - \Psi_{max}| = 0.06$ Vsec from Ψ_{max}, and includes over 50% of the total toroidal flux. The peak poloidal flux drops by approximately 35% (~ 0.06 Vsec) as the toroidal flux increases by more than a factor of 6 (~ 0.025 Vsec). Comparison of Φ curves for different $|\Psi-\Psi_{max}|$ reveals that toroidal flux is increased throughout the plasma and especially deep within the configuration (small $|\Psi-\Psi_{max}|$). There is a sharp peaking of n = 3 and 2 mode activity between t = 0.15 and 0.25 msec, precisely when the fluxes are undergoing dramatic changes. This behavior is interpreted as relaxation to a minimum energy state since I/Φ adjusts toward that for a minimum-energy state and j/B (= λ) becomes nearly uniform over the plasma volume. After formation is complete (0.4 msec), the fluxes are observed to decay slowly due to resistive losses.

Experimental observations and comparison with theoretical predictions suggest that the above modes are resonant inside the plasma and are resistive MHD unstable. A significant finding is the temporal progression of the MHD activity through an n = 5, 4, 3, 2; m = 1 mode sequence during formation. Sequences are almost always from high n to lower n. The n^{th} mode usually is decaying while the $(n - 1)^{th}$ mode is growing. Figure 2 shows a typical time progression through an n = 3, 2 mode sequence. Higher n-mode lobes are often observed to develop into lobes of the lower n-mode structures.

This progression is reminiscent of that for magnetic oscillations during the start-up phase of a tokamak plasma first observed[10] in the early 1970's. In the tokamak case, a progression of m = 6,5,4,3,2; n = 1 modes is observed as $q(\Psi)$ decreases and q = m/n rational surfaces enter the plasma; tearing modes are believed to then cause anomalous current penetration.[11]

For the S-1 Spheromak case, comparison of the time evolution of the $q(\Psi)$ profile with that of the modes also shows a close relationship. The q-value at the magnetic axis, q_o, is observed to rise through the rational fractions 1/5, 1/4, 1/3, 1/2 midway through the formation phase (Fig. 3c). The temporal evolution of the low n-number modes follows a sequence of n = 5, 4, 3, 2; m = 1 during the precise time interval q_o is rising through values equal to m/n. Once $q_o > m/n$, the m/n rational surface is inside the plasma allowing for the modes to cause a redistribution of fluxes through resistive effects.

After formation, $q(\Psi)$ is a monotonically increasing function of Ψ from the separatrix (R = ±30 cm) to q_o = 0.7 at the magnetic axis (R = ±60 cm). This general profile is then maintained for the remainder of the discharge. A classical spheromak with the same degree of oblateness as the experimental configuration is predicted to have a q_o of 0.65, with q decreasing to 0.47 at the separatrix, in agreement with experiment.

The experimentally observed temporal sequence of unstable modes agrees with resistive stability analysis.[8,9] Figure 4 shows the linear growth rate *contours*[8] *for* $m = 1$ *perturbations in the continuous space formed by* nq_o and na/R, where a and R are minor and major spheromak radii. An equilibrium profile is represented by a straight line emanating from the origin. During formation, a/R increases in time, and the two straight lines with time labels t_1 and t_2 ($t_2 > t_1$) represent two experimental equilibria when the $n = 3$ and $n = 2$ modes are observed, respectively. For t_1, the $n = 3$ mode is resistive MHD unstable while the $n = 2$ mode is stable. Although modes with higher n are more unstable, theory predicts[9] that higher n-modes nonlinearly saturate at lower amplitudes so that the lowest unstable n number is expected to be dominant. This agrees with experimental observations. For t_2, the $n = 2$ mode also becomes resistive MHD unstable. It is of additional interest that the experimental equilibria are never far from the least unstable configuration with $q_c R/a \sim 0.67$.

We have shown strong evidence that low n-number resistive MHD modes play an essential role in relaxation of the S-1 Spheromak plasma toward the Taylor state during formation, wherein there can be a large transfer of magnetic flux. The temporal evolution of modes through the $n = 5, 4, 3, 2; m = 1$ sequence parallels the rise of the experimentally measured q_o through m/n rational fractions. Experimental observations and comparison with theoretical predictions suggest that the modes observed in S-1 can provide a means for relaxation since they are resonant modes and are resistive MHD unstable.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

FIG. 1. Cross section of S-1 device showing vacuum vessel, equilibrium field coils, flux core, passive Figure-8 coil stabilization system, and the n-mode diagnostic. The experimentally obtained poloidal flux contours of a spheromak configuration toward the end of the formation phase are also shown.

FIG. 2. Mode amplitude versus time. This discharge shows a clear sequential time evolution of the (n = 3, 2) modes. Formation is completed at 0.4 msec, and discharge terminates at 0.75 msec. Toroidal dependence of B_R is shown with respect to the n = 0 component (circles) at various times in the discharge.

FIG. 3. Time evolution of (a) maximum poloidal flux Ψ_{max}, (b) toroidal flux Φ included in the poloidal flux contour a distance $|\Psi-\Psi_{max}|$ from Ψ_{max} and (c) q on the magnetic axis. There is a precipitous drop in Ψ_{max} and a concurrent sudden and large increase in Φ during the period of strong magnetic mode activity.

FIG. 4 Growth rate contours of $m = 1$ perturbations in the continuous space formed by nq_o and na/R. Growth rates are proportional to the integer labels. Stable, ideal MHD unstable, and resistive MHD unstable regions are distinguished by dashed curves. An equilibrium is represented by a straight line starting at the origin. Typical experimental equilibria during the period of strong mode activity are indicated at times t_1 and t_2 with $t_2 > t_1$.

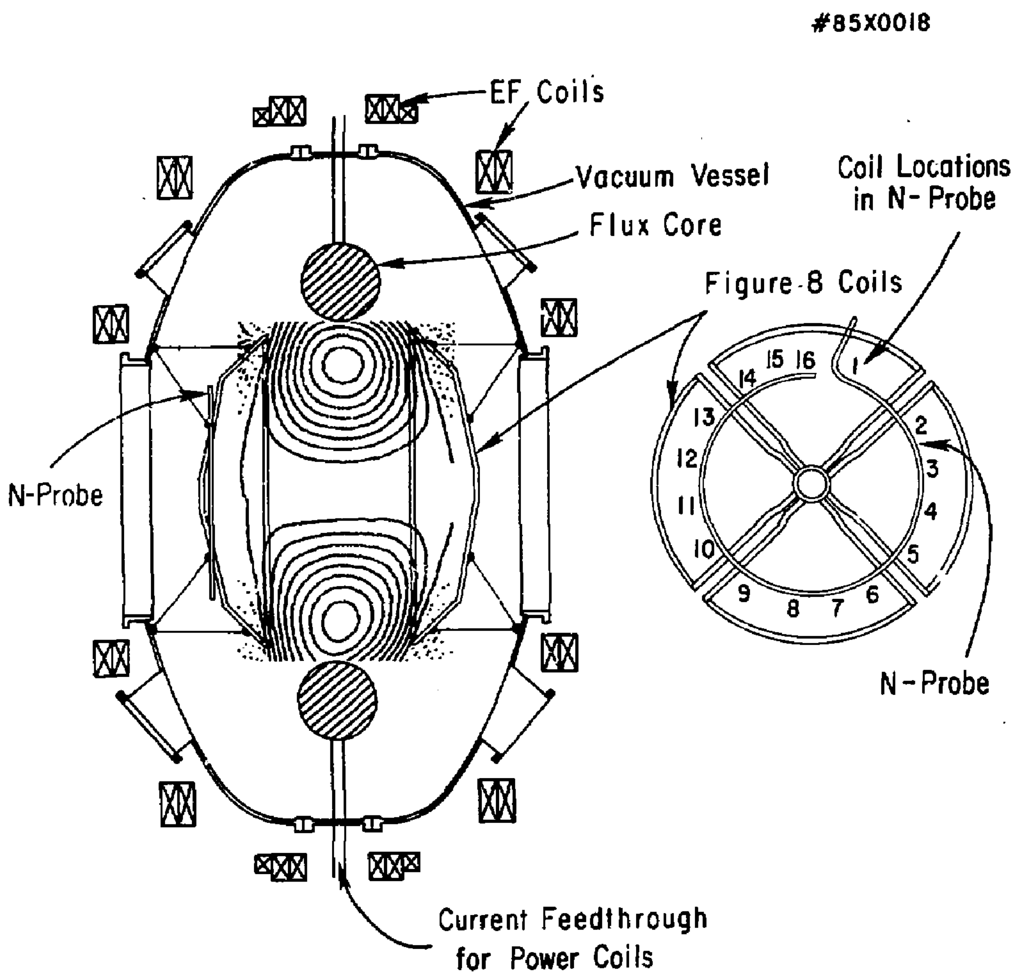
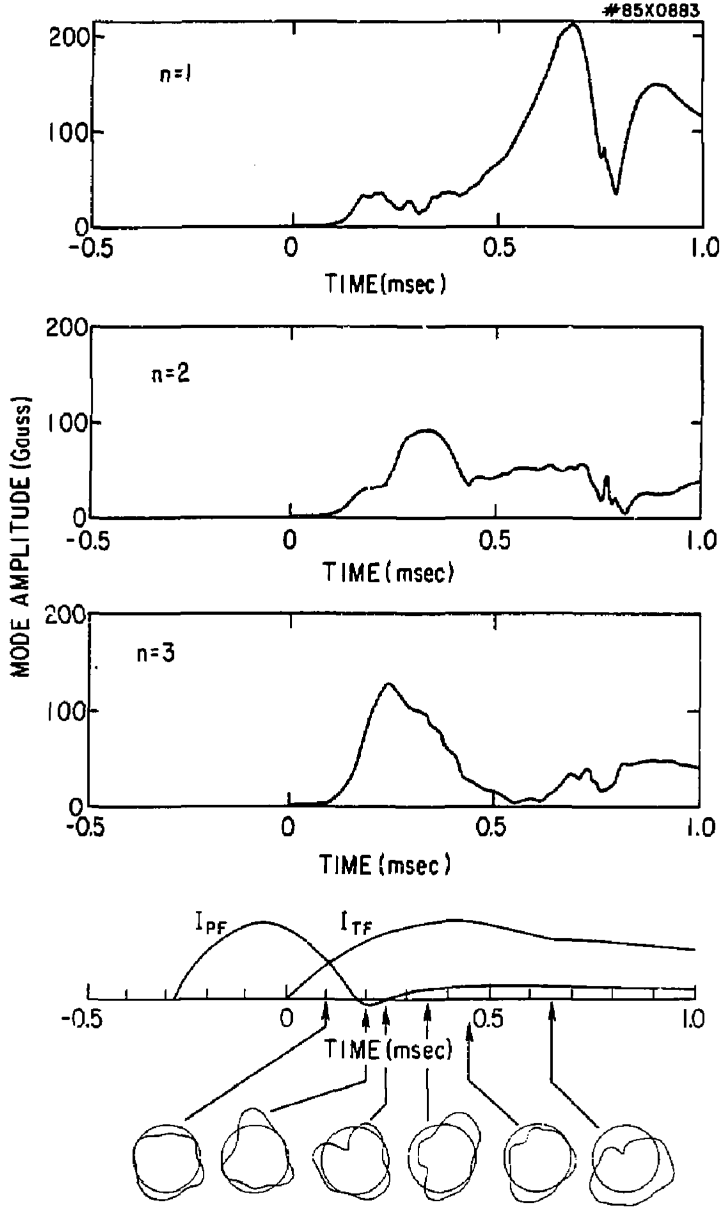

#85X0018
EF Coils
Vacuum Vessel
Flux Core
Coil Locations
in N-Probe
Figure-8 Coils
N-Probe
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
N-Probe
Current Feedthrough
for Power Coils

Fig. 1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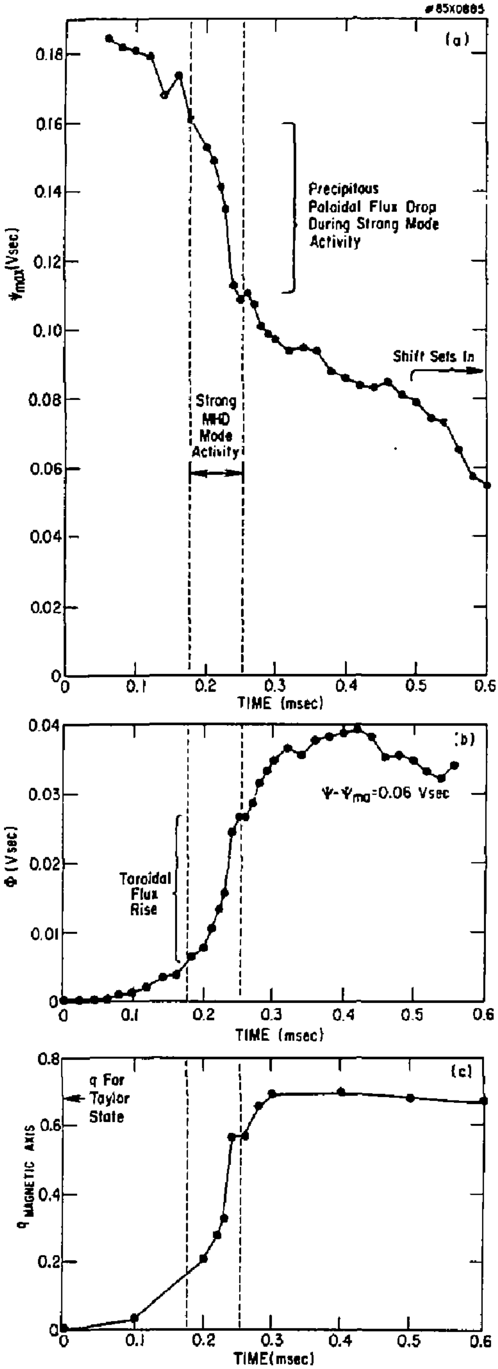
100
0
-0.5
0
0.5
1.0
TIME(msec)
n=2
TIME(msec)
n=3
TIME(msec)
MODE AMPLITUDE (Gauss)
I_{PF}
I_{TF}
TIME (msec)

Fig. 2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(a)
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0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
Ψ_{max}(Vsec)
Precipitous Poloidal Flux Drop During Strong Mode Activity
Shift Sets In
Strong MHD Mode Activity
0
0.1
0.2
0.3
0.4
0.5
0.6
TIME (msec)
(b)
0.04
0.03
0.02
0.01
0
Φ (Vsec)
Toroidal Flux Rise
Ψ-Ψ_{ma}=0.06 Vsec
0
0.1
0.2
0.3
0.4
0.5
0.6
TIME (msec)
(c)
0.8
0.6
0.4
0.2
0
q For Taylor State
$q_{MAGNETIC\ AXIS}$
0
0.1
0.2
0.3
0.4
0.5
0.6
TIME(msec)

Fig. 3

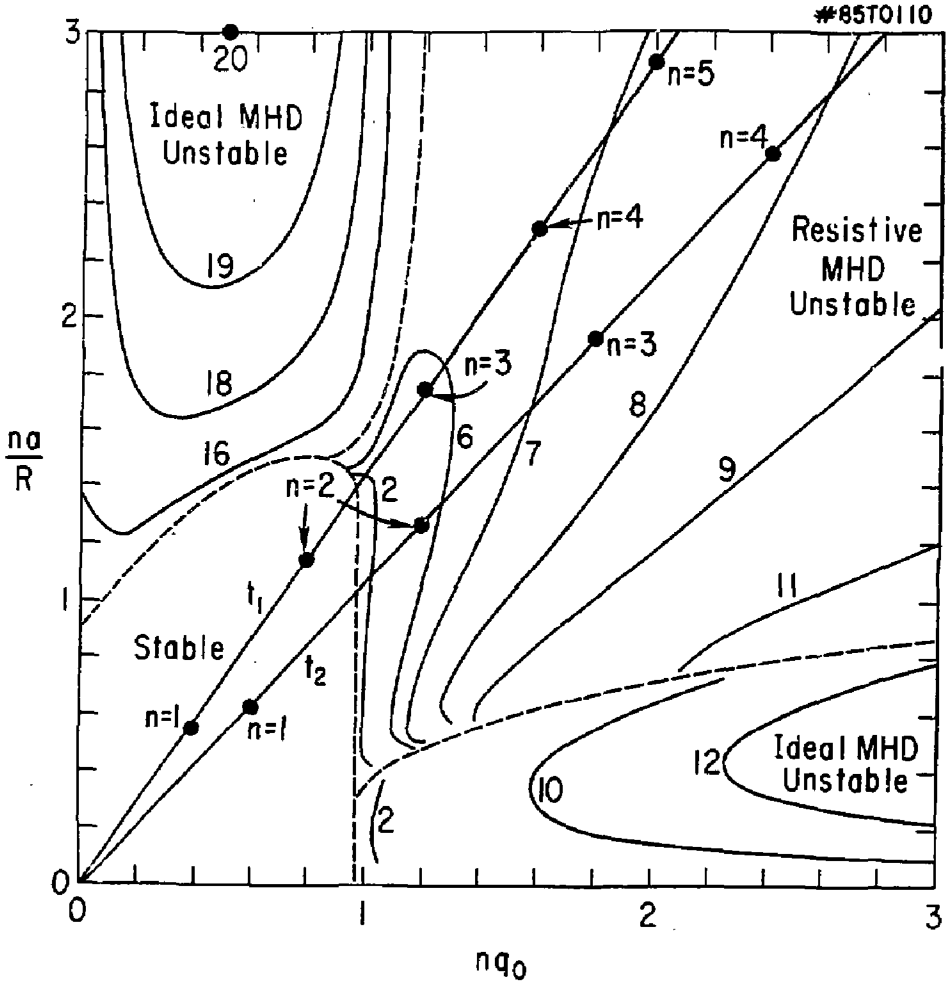
#85T0110
Ideal MHD Unstable
Resistive MHD Unstable
Stable
Ideal MHD Unstable
20
19
18
16
2
6
7
8
9
11
12
10
2
n=5
n=4
n=4
n=3
n=3
n=2
n=1
n=1
t_1
t_2
$\frac{na}{R}$
nq_0
0
1
2
3
0
1
2
3

Fig. 4

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