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ABSTRACT

We show, for q-profiles which lead to a disruption, that the control of the amplitude of the 2/1 tearing mode avoids the disruption. We have studied q-profiles measured in T-4 and PLT before a major disruption. Two methods of controlling the 2/1 mode amplitude have been considered:
1) Feedback stabilization with the feedback signal locked in phase with the 2/1 mode. The major disruption is suppressed if the feedback parameters (time delay and gain) are properly chosen. Otherwise, we observe only a delay in the disruption. 2) Heating slightly outside the q = 2 surface. Modifying the current density profile can decrease, and even eliminate, the 2/1-3/2 interaction. In this way the disruption is avoided.

In both cases it is only necessary to decrease the 2/1 mode amplitude to suppress the disruption. It is not always necessary to stabilize the unstable modes fully.

1. INTRODUCTION

During the past several years it has been suggested that the stabilization of resistive tearing modes in tokamaks would have desirable consequences. Recent nonlinear theoretical results indicate that the stabilization of the m/n = 2/1 tearing mode will improve plasma confinement [1-4] and possibly prevent major disruptions [5,6]. Specifically, it was established (Ref. [1]) that the amplitude of the m = 2, n = 1 poloidal magnetic fluctuations (Mirnov oscillations), as measured at the limiter, can be explained by the elementary nonlinear theory of the 2/1 tearing mode. Also, the confinement time has been empirically correlated with the amplitude of the m = 2 Mirnov oscillation [3,7] (as the amplitude increases, the confinement deteriorates). Thus, the stabilization of the 2/1 mode should be pursued. Furthermore, it has been shown that, for q-profiles observed prior to some major disruptions [8,9], the 2/1 and 3/2 modes are both linearly unstable. A nonlinear, three-dimensional analysis shows that the 2/1 mode further destabilizes, through mode coupling, the 3/2 mode, as well as other modes, on a rapid time scale. This results in overlapping islands of different helicities, with stochastization of field lines presumably producing a disruption [5]. This suggests that the stabilization of the 2/1 mode could provide a way of avoiding the major disruption.

In this paper the three-dimensional, nonlinear resistive magnetohydrodynamic (MHD) code RSF [10] has been used to study numerically two methods of stabilization of the 2/1 mode:

1) Feedback stabilization [11]. A feedback mechanism can be used to stabilize the 2/1 tearing mode if the mode and the feedback signal are locked in phase at the limiter. However, the feedback parameters (time delay and gain) must be properly chosen for the method to work.
2) Heating outside the q = 2 surface. This method, suggested in Ref. [12], is the result of a linear analysis. Our analysis shows that the growth rates and single helicity saturation amplitudes of the 2/1 and 3/2 modes decrease when the temperature (current density) increases

outside the q = 2 surface. By modifying the current density in this manner, we can decrease, and even eliminate, the 2/1-3/2 interaction. In this way a major disruption could be avoided.

Because the computer code RSF [10] can deal with mixed helicity problems, we can follow the effects of the stabilization of the 2/1 on its nonlinear interaction with other modes. This allows us to see its effect on the disruption.

There are some experimental results [13,14] which show agreement with our numerical studies, giving further encouragement to this line of research.

The general method of feedback stabilization, together with linear results, is presented in Section 2. The nonlinear results for profiles likely to produce a major disruption are discussed in Section 3. In Section 4 we present the method of profile modification, and our conclusions are summarized in Section 5.

2. FEEDBACK STABILIZATION: LINEAR THEORY

We have studied the stabilization of the 2/1 tearing mode using the reduced set of resistive MHD equations introduced in Ref. [15]. They were derived for low β plasmas having large ratios of toroidal to poloidal magnetic fields. In cylindrical geometry they are (see appendix):

$$D\psi/Dt = \eta J_\zeta - E^w_\zeta - \partial\phi/\partial\zeta \tag{1}$$

$$DU/Dt = -S^2[\hat{\zeta}\cdot(\underline{\nabla}\psi \times \underline{\nabla}J_\zeta) + \partial J_\zeta/\partial\zeta] \tag{2}$$

In the single helicity approximation, these equations reduce to those used in previous work [16,17]. They do not contain diamagnetic drifts or other finite gyroradius effects [18], but recent results indicate that the nonlinear development of the 2/1 tearing mode is not substantially affected by diamagnetic drifts [19]. Thus, this set of equations is appropriate for a preliminary investigation of feedback stabilization. Most of the results presented in this paper correspond to locking the phase between the mode and the feedback signal. In some cases we have simulated a variable phase shift between the mode and the feedback signal by a rigid rotation of the whole plasma. This process leads to negative results. The necessity of locking the feedback signal and the 2/1 mode in phase for the single helicity approximation is pointed out in Ref. [20].

To gain insight into the problem, we found it useful to begin with a linear analysis. This corresponds to an ideal feedback having a time delay t_D of zero. The singular (mode rational) surface is defined by the radius r_{mn} at which $q(r_{mn}) = m/n$. For values of r such that $|r - r_{mn}|$ is larger than the tearing layer width, the inertial term is unimportant. In this case Eq. (2) yields [21]

$$\left(\frac{d\psi_o}{dr}\frac{m}{r} + n\right) J_{mn} = \frac{m}{r}\frac{dJ_o}{dr}\psi_{mn} \tag{3}$$

where the o subscript denotes unperturbed quantities and $J_{mn}(\psi_{mn})$ is the perturbed current (flux). In the absence of a feedback signal, this singular equation is solved with these boundary conditions: $\psi_{mn}(a) = 0$, ψ_{mn} regular at $r = 0$, and ψ_{mn} continuous at r_{mn}. Due to the singularity at r_{mn}, the quantity

$$\Delta'_{mn} = \lim_{\delta \to 0} \left(\frac{d\psi_{mn}}{dr} \bigg|_{r^+_{mn}} - \frac{d\psi_{mn}}{dr} \bigg|_{r^-_{mn}} \right) \bigg/ \psi_{mn}(r_{mn}) \tag{4}$$

is nonzero. Here $r^{\pm}_{mn} = r_{mn} \pm \delta$. The tearing mode is stable if $\Delta'_{mn} \leq 0$.

Inclusion of a feedback signal alters the above boundary conditions to allow nonzero values of $\psi_{mn}(a)$. The condition for marginal stability remains $\Delta'_{mn} = 0$, so that feedback stabilization consists of controlling the value of Δ'_{mn} through the boundary condition $\psi_{mn}(a)$. The value of $\psi_{mn}(a)$ which results in $\Delta'_{mn} = 0$ can be used to calculate the magnetic field which must be applied by the feedback system to stabilize the mode in this ideal case.

As an example, using flat current profiles [21] for which

$$q = 2 \sqrt[4]{\frac{1 + (r/r_o)^8}{1 + (r_{21}/r_o)^8}}$$

we have evaluated the relative amplitude of the feedback signal, i.e., the value of $\beta_o \equiv \psi_{21}(a)/\psi_{21}(r_{21})$, for which Δ'_{21} vanishes. The results are presented in Fig. 1, where β_o versus r_{21} has been plotted for three fixed values of r_o. The q-profile obtained from fitting the electron temperature profile measured in the Princeton Large Torus (PLT) [8] (see appendix) prior to a major disruption has $\beta_o = -6.9$ for marginal stability, and simulation of this case has been carefully studied in Refs [5,6,15]. Figure 2 shows the time evolution of the 2/1 mode for this profile using different values of β_c. There is good agreement between the value of β_o obtained from the condition $\Delta'_{21} = 0$ and the one which gives zero growth rate for this mode.

3. FEEDBACK STABILIZATION: NONLINEAR RESULTS

The effect of the feedback stabilization of the 2/1 tearing mode on a major disruption has been studied using RSF [10], a three-dimensional, nonlinear resistive MHD code. The interaction of modes of different helicities is considered in RSF, making it an appropriate tool for the study of the major disruption.

Two equilibrium q-profiles, one characterizing PLT [8] and the other T-4 [22] prior to a major disruption, were considered. Realistic values for S were used, namely $S = 4 \times 10^5$ for T-4 and $S = 10^6$ for PLT (see appendix for details).

As described in Section 2, the relative phases of the 2/1 mode and the feedback signal were locked. A time delay t_D between the 2/1 signal and the feedback response was assumed. The effect of the feedback signal was incorporated as a boundary condition upon the poloidal magnetic flux ψ_{21}:

$$\psi_{21}(r = a, t) = \beta(t)\ \psi_{21}(r = r_{21},\ t - t_D) \qquad (5)$$

where $\beta(t)$ performs the role of β_o as described in Section 2.

In both T-4 and PLT, stabilization of the 2/1 mode with finite t_D could not be achieved unless the feedback signal was periodically switched on and off. Otherwise, feedback caused the relative phases of ψ_{21} at the present and the delayed times to flip, leading the feedback signal to drive, rather than stabilize, the mode. To surmount this problem, the feedback signal was periodically switched on and off, thus allowing the 2/1 mode to resume an eigenmode shape during the "off" period before modifying its shape through feedback during the "on" period. Using this scheme, we took the expression for $\beta(t)$ to be

$$\beta(t) = \beta_o f(t)\ g(t)$$

where

$$f(t) = \begin{cases} e^{\gamma_{21}(t_D+t_{on}-t)}, & t_{on} \leqslant t \leqslant t_{on} + t_D \\ 1, & t_{on} + t_D \leqslant t \end{cases}$$

and

$$g(t) = \begin{cases} 1 - e^{-(t-t_{on})/\tau_{on}}, & t_{on} \leqslant t \leqslant t_{off} \\ \left|1 - e^{-(t-t_{on})/\tau_{on}}\right| e^{-(t-t_{off})/\tau_{off}}, & t_{off} < t \end{cases}$$

We have plotted this function $\beta(t)$ in Fig. 3. The function $f(t)$ enhances the feedback signal by a factor equal to the linear growth of the 2/1 mode between the time at which the signal is taken $(t - t_D)$ and the time at which the feedback is initialized (t_{on}). In this formulation, γ_{21} represents the linear growth rate of the 2/1 eigenmode, and t_{on} is the time at which the feedback signal is switched on. The function $g(t)$ represents the switching on and off of the feedback signal. The signal is turned on at time t_{on} with a characteristic rise time τ_{on} and turned off at t_{off} with a decay time τ_{off}. The "on time" is just $t_{off} - t_{on} \equiv \Delta t_{on}$ and is taken to be a fixed constant. The "off time" Δt_{off} between t_{off} and the next switch on at a new t_{on} is also taken to be a fixed constant. We have taken $\Delta t_{on} = \Delta t_{off} \gg \tau_{on}, \tau_{off}$ in this work.

The feedback parameters to which the 2/1 mode is sensitive are the amplitude β_o, the time delay t_D, and the switching period $\Delta t = \Delta t_{on} + \Delta t_{off}$. We have found for a variety of cases that the best choice of switching period is $\Delta t = 2 \times t_D \approx \gamma_{21}^{-1}$. This means the 2/1 tearing mode is used to generate a feedback signal only at times when it is not subjected to such a signal. Initial estimates for β_o can be obtained from linear theory (see Section 2).

Figure 4 shows the variation of the 2/1 island width with time for the T-4 q-profile for several values of β_o at a time delay $t_D = 160\ \tau_{Hp} = 1.2\ \gamma_{21}^{-1}$ (all times will be expressed in poloidal MHD units). Linear theory predicts $\beta_o = -2.2$ for marginal stabilization in this case. We see that for no feedback stabilization the island width grows and a disruption eventually occurs. (The disruption is indicated in the figure by the vertical line). For $\beta_o = -3.4$, the island width oscillates with growing amplitude until a disruption occurs. For the intermediate values of $\beta_o = -1.6$ and $\beta_o = -2.5$, the 2/1 mode is stabilized as the island width oscillates within a finite range. In the best case $\beta_o = -2.5$, which is close to the marginal stability value given by linear theory. Figure 5 shows the analogous results for the PLT q-profile using a value of $t_D = 200\ \tau_{Hp} = 0.9\ \gamma_{21}^{-1}$. In this case the linear theory estimate of β_o is -7. Again the nonstabilized 2/1 mode grows until disruption occurs. For the linear theory value of $\beta_o = -7$, the 2/1 mode grows. The largest value of $\beta_o = -15$, considered in Fig. 5, does not lead to a disruption, but the oscillations of the island width have larger peak values than for the best case ($\beta_o = -12$). The results suggest that there is an optimal range for the gain of the feedback signal. Too intense a feedback signal can have destabilizing effects on the 2/1 mode while too weak a feedback signal is insufficient for stabilization of the mode, i.e., $1.5 \leqslant -\beta_o \leqslant 3.2$ for T-4 case.

Let us consider a feedback system, similiar to the Adiabatic Toroidal Compressor (ATC) feedback system [14], consisting of two $\ell = 2$ helical coils inside the vacuum vessel. The current intensity needed in the coils to stabilize the 2/1 mode is given by

$$I \cong \frac{\pi}{16\mu_o} \frac{ba}{R} B_z \left(\frac{w_{21}}{a}\right)^2 \frac{r_{21} q^1(r_{21})}{q} |\beta|$$

where b is the radial position of the helical coils. For PLT parameters our calculations indicate that the current I should be between 1.7 kA and 3.7 kA and for T-4 between 0.8 kA and 3 kA. These values are only estimations, and more accurate values depend on the specific design of the feedback system.

Figure 6 shows the effect of the delay time t_D on the stability of the 2/1 mode. The 2/1 magnetic island width is plotted as a function of time for several runs having $\beta_o = -2.5$ in T-4. For $t_D = 0$, the 2/1 island width quickly goes to zero and stays zero. For $t_D = 160\ \tau_{Hp} = 1.2\ \gamma_{21}^{-1}$, the 2/1 is again stabilized in the sense that the island width remains small. However, for $t_D = 280\ \tau_{Hp} = 2.1\ \gamma_{21}^{-1}$ and $t_D = \infty$ (no feedback stabilization), a disruption occurs. If the time delay of the feedback signal is not kept small enough, we observe only a delay in the disruption. As a general result, we can say that the time delay should be

$$t_D \lesssim \gamma_{21}^{-1}$$

where γ_{21} is the linear growth rate of the 2/1 tearing mode.

It is informative to compare the island widths of the 2/1 and 3/2 modes for runs with feedback and without feedback. Figure 7 shows the 2/1 and 3/2 magnetic island widths as functions of time for both runs with feedback ($\beta_o = -2.5$, $t_D = 160\ \tau_{Hp}$) and runs without feedback for the T-4 equilibrium q-profile. Figure 8 shows a very similar behavior for the PLT q-profile. For both the T-4 and PLT profiles, the 3/2 island width saturates at its single helicity saturation value as long as the amplitude of the 2/1 tearing mode is kept sufficiently small. That is, when we control the island width of the 2/1 mode in such a way that the 2/1 island does not touch the 3/2 island, the coupling between these two modes is negligible. There is, in this case, no further destabilization of the 3/2 mode which would lead to the disruption.

We have simulated the effect of a nonzero phase shift between the feedback signal and the 2/1 mode by a rigid body rotation of the whole plasma. In this case we have not succeeded in stabilizing the 2/1 mode, and, of course, the disruption has not been avoided.

We can underline the effect of feedback by showing the magnetic field lines when the 2/1 tearing mode is controlled by the feedback signal. In Fig. 9, we show the field lines at the end of the two runs presented in Fig. 7. When the feedback signal is off (Fig. 9a), there is a stochastic region covering about half of the plasma. But with the feedback system on, practically no magnetic surfaces are destroyed. The anticipated improvement in confinement is quite apparent. In Fig. 10 similar results are shown for the runs presented in Fig. 8 (PLT case).

4. CONTROLLING THE CURRENT PROFILE NEAR THE q = 2 SURFACE

Another way to control the amplitude of the 2/1 tearing mode is to modify the current profile near the q = 2 singular surface by raising the temperature outside the q = 2 surface.

From Eq. (3) it is clear that the tearing instability in the linear regime is driven by the gradient of the equilibrium current near the singular surface. We have investigated the possibility of controlling the 2/1 tearing mode by decreasing the gradient of the current density at the q = 2 surface. This method, suggested in Ref. [12], is a result of a linear analysis, and we have pursued it in the nonlinear regime. We assume that this modification of the current profile can be produced by increasing the electron temperature outside the q = 2 surface. We have made this modification in the current profile in an ad hoc way without generating the profiles self-consistently. This introduces a limitation in our study, and it does not allow us to investigate the sensitivity of the method to the parameters relevant to its implementation, as we did for the feedback method.

The nonlinear results show that the suppression of the major disruption does not require, in general, a careful tailoring of the current profile. It is sufficient to modify the current profile in such a way that the magnetic islands of the 2/1 and 3/2 tearing modes do not touch. This can be achieved by increasing the current outside the q = 2 surface. When the profile under consideration is very unstable to the 2/1 tearing mode, as in the case of the PLT current profile, we have to practically flatten the current profile at the q = 2 surface.

In Fig. 11 we have plotted the current profiles we have considered, which correspond to different modifications of the PLT current profile (profile 1). For these profiles we present in Fig. 12 the time evolution of the 3/2 magnetic island width. Although a simple increase in the temperature outside the q = 2 surface (case 2) can delay the disruption, it does not avoid it. To suppress the disruption, it is necessary to practically flatten the current profile at the q = 2 surface.

To understand better the effect of the profile modification on the 2/1-3/2 interaction, we have used a simple parameterization of the q-profile

$$q = q(0)\ [1 + (r/r_o)^{2\lambda}]^{1/\lambda} \tag{6}$$

where $\lambda = \lambda_o + 1/2\lambda''r^2$. We held q(0) and q(1) fixed at 1.08 and 4.0 respectively and used λ_o and λ'' as free parameters. We can modify the gradient of the current profile in different ways and study its effect on the nonlinear interaction of the 2/1 and 3/2 tearing modes. As a measure of this interaction, we use the peak value of the growth rate of the 3/2 mode [5,23]. Another interesting parameter to calculate is

$$d \equiv r_{21} - r_{32} - \frac{1}{2}\,(W_{21} + W_{32})$$

where W_{21} and W_{32} are the single helicity saturated widths for the 2/1 and 3/2 tearing modes respectively. For the cases we have considered, we found that there is a strong nonlinear interaction when $d < 0$.

The results of our analysis are summarized in Figs 13 and 14. In Fig. 13 we present the results for λ'' held fixed to 0 and $0 \leqslant \lambda_o \leqslant 4$. As λ_o increases, the current profile flattens near the magnetic axis while near the singular surface it becomes steeper. For $\lambda_o \geqslant 2.2$, d is negative and the nonlinear evolution leads to a disruption. When we hold λ_o fixed to 2 and vary λ'', we obtain similar results, as shown in Fig. 14.

As a general result of this analysis, we conclude that the modification of the current profile should give

$$r_{21} - r_{32} > \frac{1}{2}\,(W_{21} + W_{32})$$

to suppress the disruption.

If the modification of the current profile is in the wrong place, that is, if we increase the current density inside the q = 2 surface, the 2/1 mode is more strongly destabilized. Therefore, it is important to study how to modify the profiles. Some recent experimental results from the JIPP T-II tokamak [13], using this technique to control the disruption, show positive results.

5. CONCLUSION

The nonlinear interaction of the 2/1 and 3/2 tearing modes, which is a possible cause of major disruptions in tokamaks, can be suppressed by controlling the amplitude of the 2/1 mode either by feedback stabilization or by heating the plasma edge.

If a feedback mechanism is used to stabilize the 2/1 mode, the feedback signal should be locked in phase with this mode. The time delay of the system should be smaller than γ_{21}^{-1}. The gain of the feedback system should be near the value given by the linear theory for marginal stability. For the PLT and T-4 tokamaks, this implies currents in the feedback coil of the order of 2 kA and 1 kA respectively. Unless the parameters lie in this range, the disruption will not be suppressed, but only delayed.

An alternative technique is controlling the current profiles near the $q = 2$ surface in such a way that

$$|r_{21} - r_{32}| > \frac{1}{2} (W_{21} + W_{32})$$

But to fully establish the feasibility of this technique, it is necessary to investigate the transport effects on the generation of these current profiles.

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APPENDIX

In three-dimensional cylindrical geometry, the resistive MHD equations are (in dimensionless form) [15],

$$\frac{D\psi}{Dt} \equiv \frac{\partial \psi}{\partial t} + \underline{v}_\perp \cdot \underline{\nabla}_\perp \psi = \eta J_\zeta - E_\zeta^w - \frac{\partial \phi}{\partial \zeta}$$

$$\frac{DU}{Dt} \equiv \frac{\partial U}{\partial t} + \underline{v}_\perp \cdot \underline{\nabla}_\perp U = -S^2 \left[\hat{\zeta} \cdot (\underline{\nabla}_\perp \psi \times \underline{\nabla}_\perp J_\zeta) + \frac{\partial J_\zeta}{\partial \zeta} \right]$$

where the subscript $\perp$ denotes quantities taken perpendicular to the toroidal direction $\hat{\zeta}$, ψ is the poloidal flux function, ϕ is the velocity stream function, $J_\zeta = \nabla_\perp^2 \psi / \mu_o$ is the toroidal current density, and $U = \nabla_\perp^2 \phi$ is the vorticity. The parameter S is the ratio of the resistive diffusion time τ_R [$\equiv \mu_o a^2/\eta(0)$, where $\eta(0)$ is the resistivity at the plasma center] to the poloidal MHD time τ_{Hp} ($\equiv R_o/V_A$, where R_o is the major radius and V_A is the Alfvén velocity). The resistivity $\eta(r)$ is assumed to be constant in time and is given by $E_\zeta^w / J_{\zeta o}(r)$, where the o subscript denotes equilibrium quantities and E_ζ^w is the electric field at the wall (limiter).

The magnetic field is given by

$$B = -\frac{a}{R_o} \underline{\nabla} \psi \times \hat{\zeta} + B_\zeta \hat{\zeta}$$

and the fluid velocity is given by

$$\underline{v}_\perp = \underline{\nabla} \phi \times \hat{\zeta}$$

Details on the numerical scheme and time advancement of these equations can be found in Ref. [10]. The parameterization for the q-profile for T-4 is obtained from the parameterization of the electron temperature profile given in Ref. [22], and it is

$$q(r) = \frac{1.25}{1 - r^4 + 0.6r^8 - 0.1428r^{12}}$$

For the PLT equilibrium q-profile, we have fitted the electron temperature profile given in Ref. [8] with the expression for q:

$$q(r) = q(0)\ [1 + (r/r_o)^{2\lambda}]^{1/\lambda}$$

The values of the parameters are q(0) = 1.34, r_o = 0.56, and λ = 3.24.

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FIGURE CAPTIONS

FIG. 1. Relative amplitude of the feedback signal $[(\beta_o \equiv \psi_{21}(1)/\psi_{21}(r_{21})]$ required by linear theory for marginal stability versus the radius of the 2/1 singular surface for three flat profiles

$$q = 2\left[\frac{1 + (r/r_o)^8}{1 + (r_{21}/r_o)^8}\right]^{1/4}$$

given by $r_o = 0.4$, 0.5, and 0.6.

FIG. 2. The 2/1 growth rate versus time for three values of β_o for an equilibrium q-profile characterizing PLT prior to a disruption.

FIG. 3. The function $\beta(t)$, characteristic feedback signal, versus time for PLT parameters. ($\beta_o = 12$, $\Delta t_{on} = \Delta t_{off} = t_D = 200\ \tau_{Hp}$). This function is compared to the evolution of the 2/1 magnetic island width when the feedback signal is on.

FIG. 4. Magnetic 2/1 island widths are plotted versus time for several values of β_o and an equilibrium q-profile characterizing T-4 prior to a disruption. All curves are for delay time $t_D = 160\ \tau_{Hp}$. For $\beta_o = 0$ and -3.4, disruptions terminate the runs.

FIG. 5. This figure is analogous to Fig. 4 except that the q-profile characterizes PLT and the delay time in $t_D = 200\ \tau_{Hp}$. A disruption terminates the $\beta_o = 0$ run.

FIG. 6. Magnetic 2/1 island widths are plotted versus time for several values of t_D for the T-4 equilibrium q-profile. All curves are for feedback amplitude $\beta_o = -2.5$. For $t_D = 280\ \tau_{Hp}$ and $t_D = \infty$, disruptions terminate the runs.

FIG. 7. Magnetic island widths of the 2/1 and 3/2 modes are plotted as functions of time for unstabilized and stabilized runs using the T-4 equilibrium q-profile. For the stabilized run, $\beta_o = -2.5$, and $t_D = 160\ \tau_{Hp}$. The unstabilized run terminates in a disruption.

FIG. 8. This figure is analogous to Fig. 7 except that the PLT equilibrium q-profile is used. For the stabilized run, β_o = -12 and t_D = 200 τ_{Hp}. As in the T-4 case, the unstabilized run disrupts.

FIG. 9. Magnetic field line configurations at the end of the two T-4 q-profile runs presented in Fig. 7.

FIG. 10. Magnetic field line configurations at the end of the two PLT q-profile runs presented in Fig. 8.

FIG. 11. Current profiles obtained by modifying the PLT q-profile outside the q = 2 surface.

FIG. 12. The 3/2 magnetic island width versus time for the three profiles considered in Fig. 11.

FIG. 13. (a) The maximum of the 3/2 growth rate as a measure of the strength of the nonlinear coupling versus λ_o. For the profile given by Eq. (6), we held q(0) = 1.08, q(1) = 4, and λ'' = 0 fixed. (b) The parameter d versus λ_o for the same runs.

FIG. 14. (a) The maximum of the 3/2 growth rate and (b) the parameter d versus λ''. We held fixed q(0) = 1.08, q(1) = 4, and λ_o = 2.

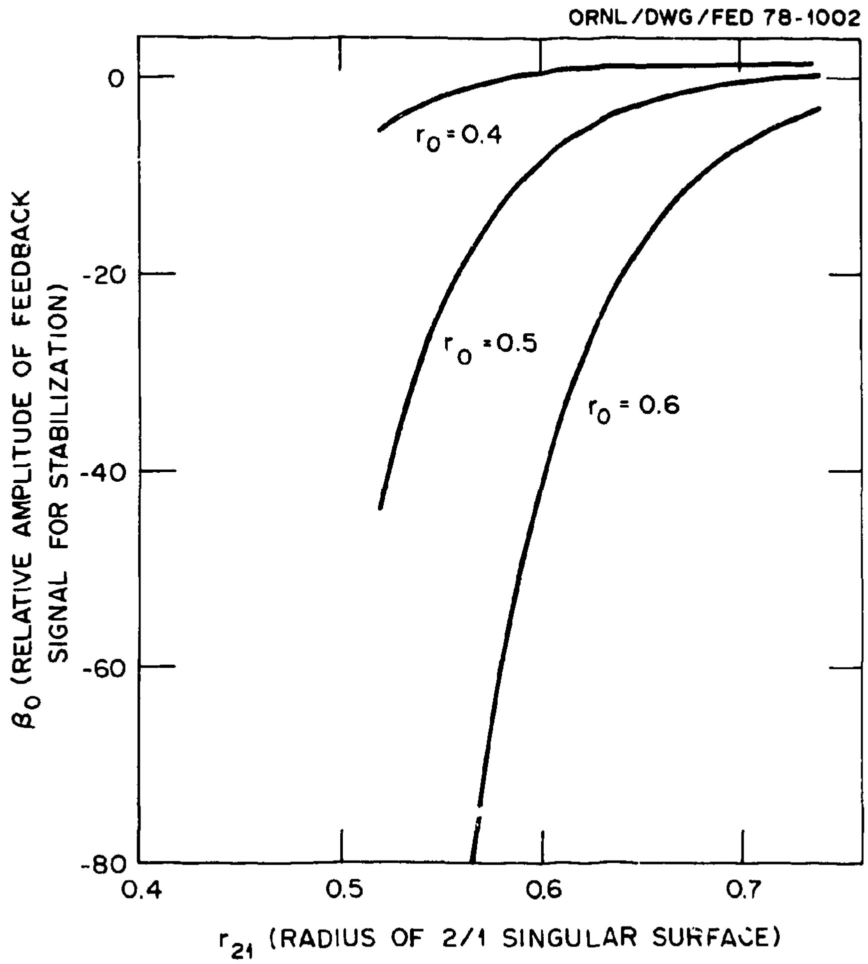

ORNL/DWG/FED 78-1002
0
-20
-40
-60
-80
0.4
0.5
0.6
0.7
r0 = 0.4
r0 = 0.5
r0 = 0.6
β0 (RELATIVE AMPLITUDE OF FEEDBACK SIGNAL FOR STABILIZATION)
r21 (RADIUS OF 2/1 SINGULAR SURFACE)

Fig. 1.

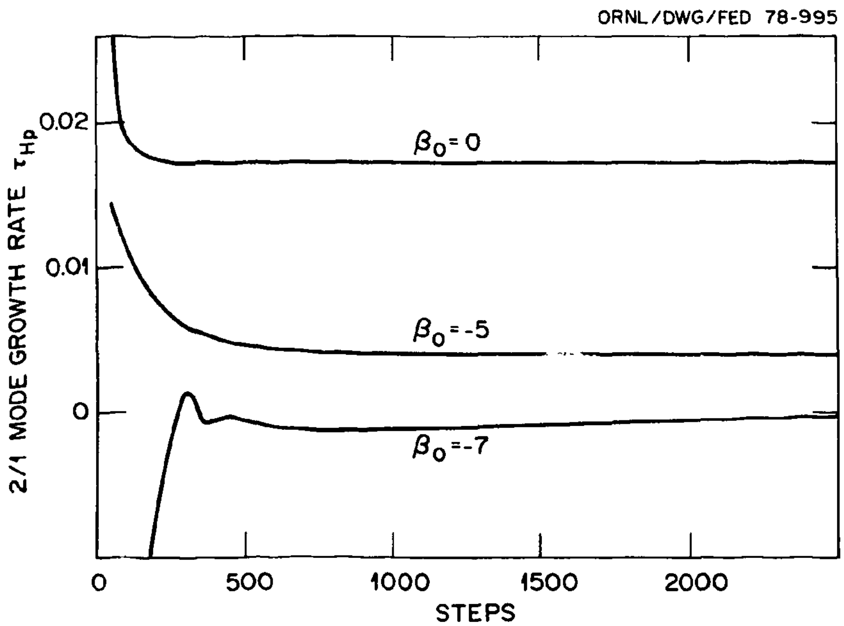

ORNL/DWG/FED 78-995
2/1 MODE GROWTH RATE τ_{Hp}
0.02
0.01
0
$\beta_0 = 0$
$\beta_0 = -5$
$\beta_0 = -7$
0
500
1000
1500
2000
STEPS

Fig. 2.

ORNL/DWG/FED 78-1190

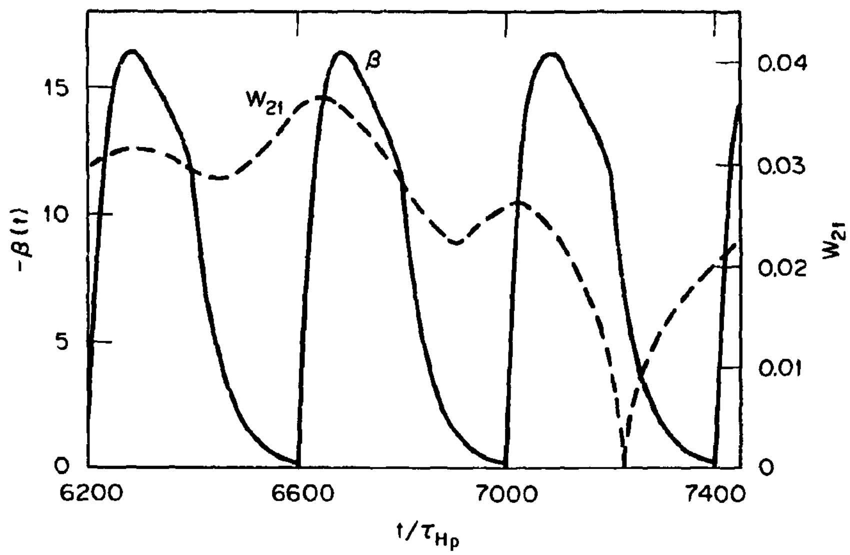


Fig. 3.

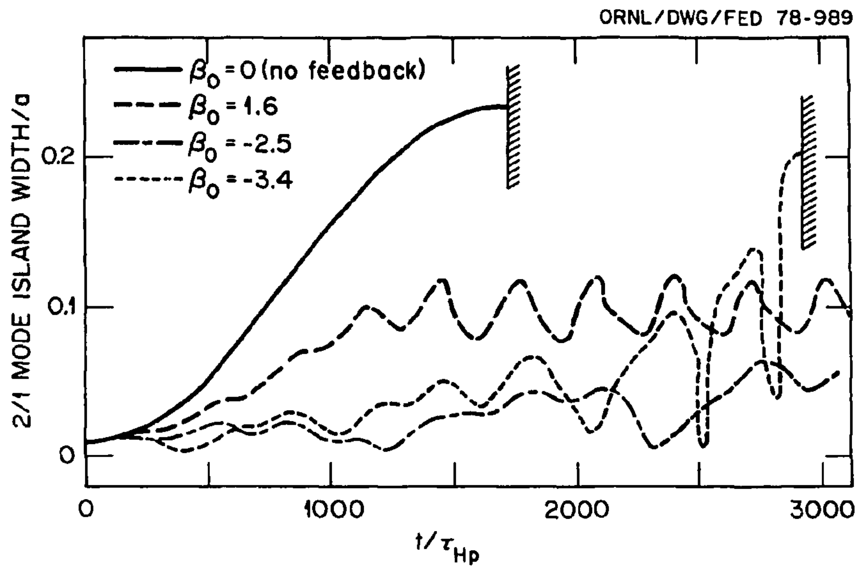

ORNL/DWG/FED 78-989
β0 = 0 (no feedback)
β0 = 1.6
β0 = -2.5
β0 = -3.4
2/1 MODE ISLAND WIDTH/a
0.2
0.1
0
0
1000
2000
3000
t/τHp

Fig. 4.

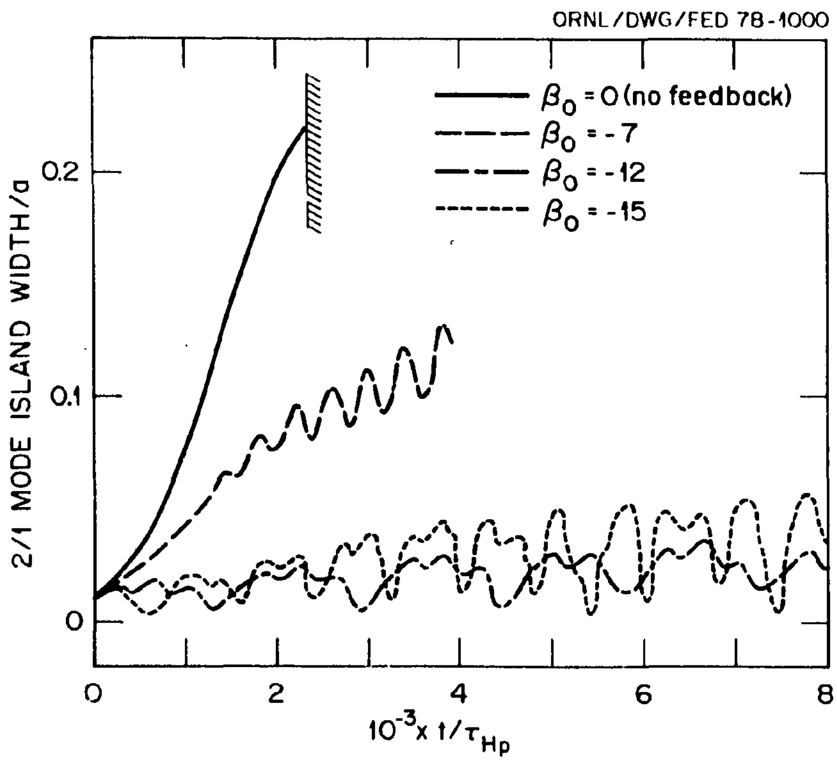

ORNL/DWG/FED 78-1000
β_0 = 0 (no feedback)
β_0 = -7
β_0 = -12
β_0 = -15
2/1 MODE ISLAND WIDTH/a
0.2
0.1
0
0
2
4
6
8
$10^{-3} \times t/\tau_{Hp}$

Fig. 5.

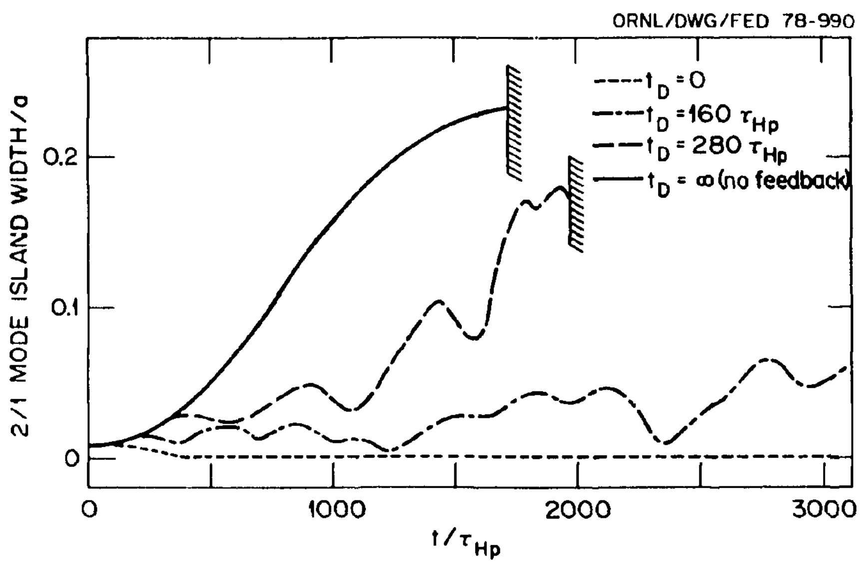

ORNL/DWG/FED 78-990
$t_D = 0$
$t_D = 160\ \tau_{Hp}$
$t_D = 280\ \tau_{Hp}$
$t_D = \infty$ (no feedback)
2/1 MODE ISLAND WIDTH/a
0
0.1
0.2
0
1000
2000
3000
t/τ_{Hp}

Fig. 6.

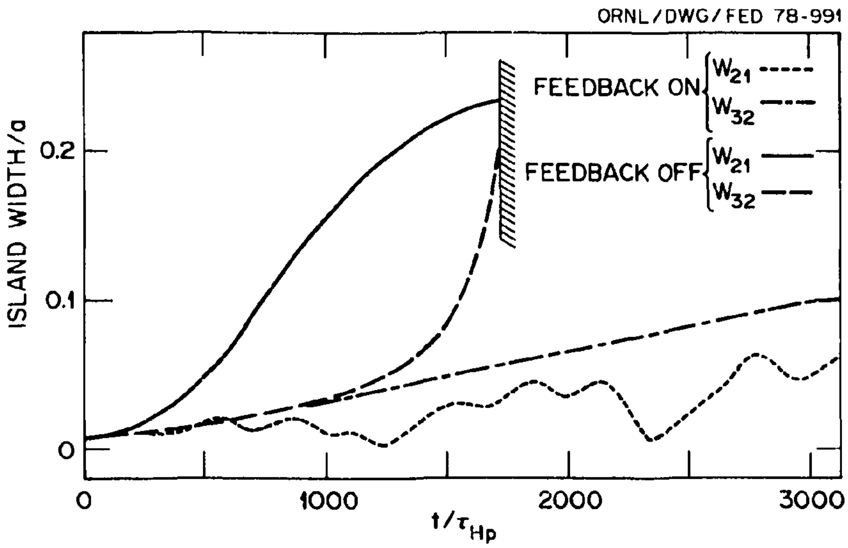
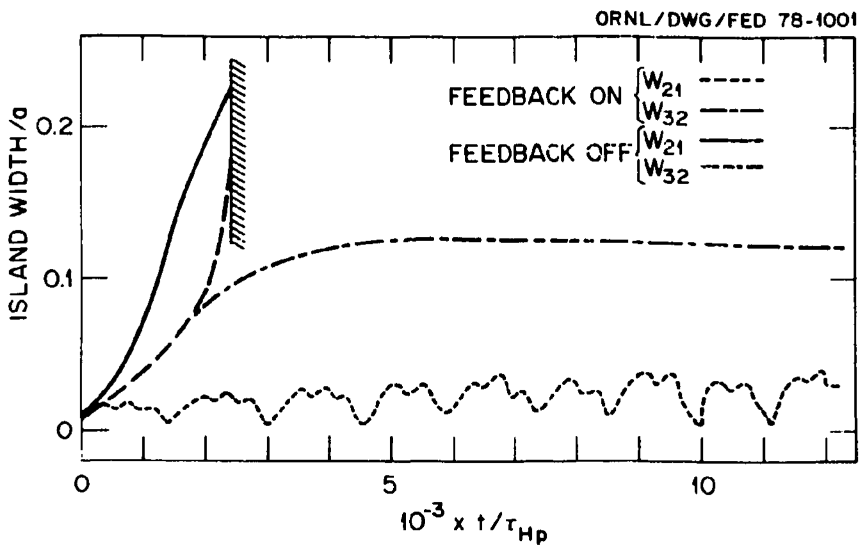

ORNL/DWG/FED 78-991
FEEDBACK ON
W21
W32
FEEDBACK OFF
W21
W32
ISLAND WIDTH/a
0.2
0.1
0
0
1000
2000
3000
t/τHp

Fig. 7.



ORNL/DWG/FED 78-1001
FEEDBACK ON
W21
W32
FEEDBACK OFF
W21
W32
ISLAND WIDTH /a
0.2
0.1
0
0
5
10
10-3 x t/τHp

Fig. 8.

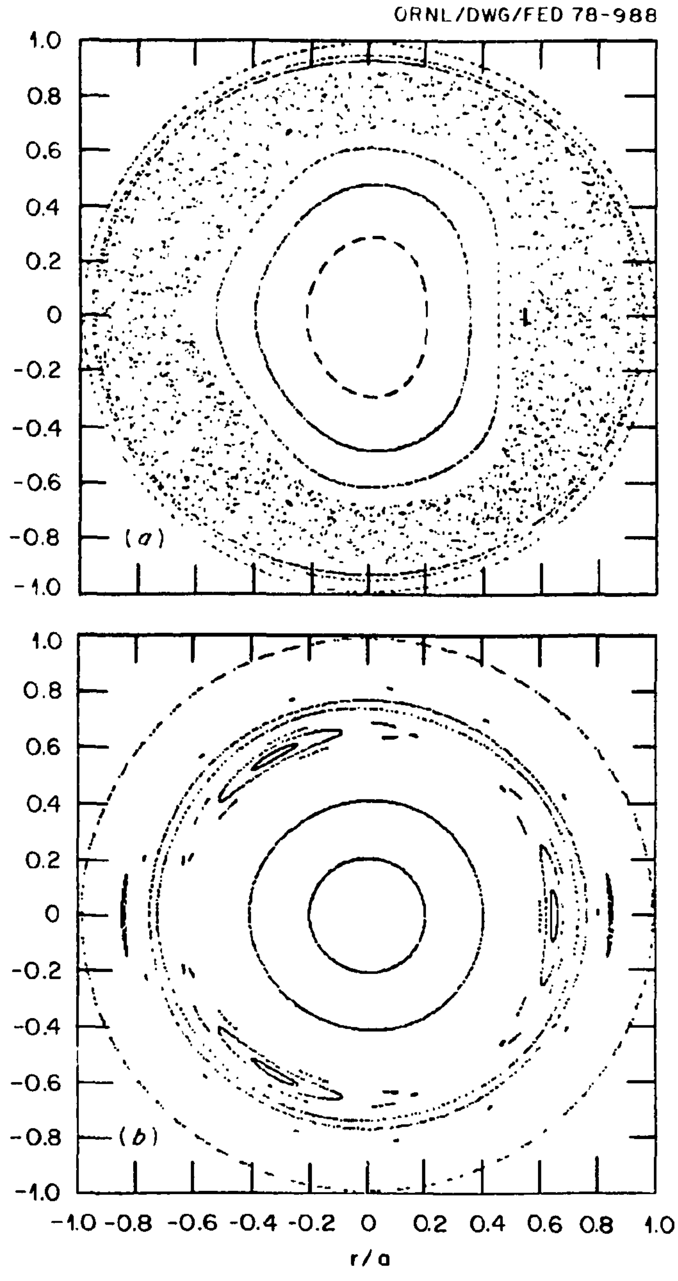

ORNL/DWG/FED 78-988
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
(a)
(b)
-1.0 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0
r/a

Fig. 9.

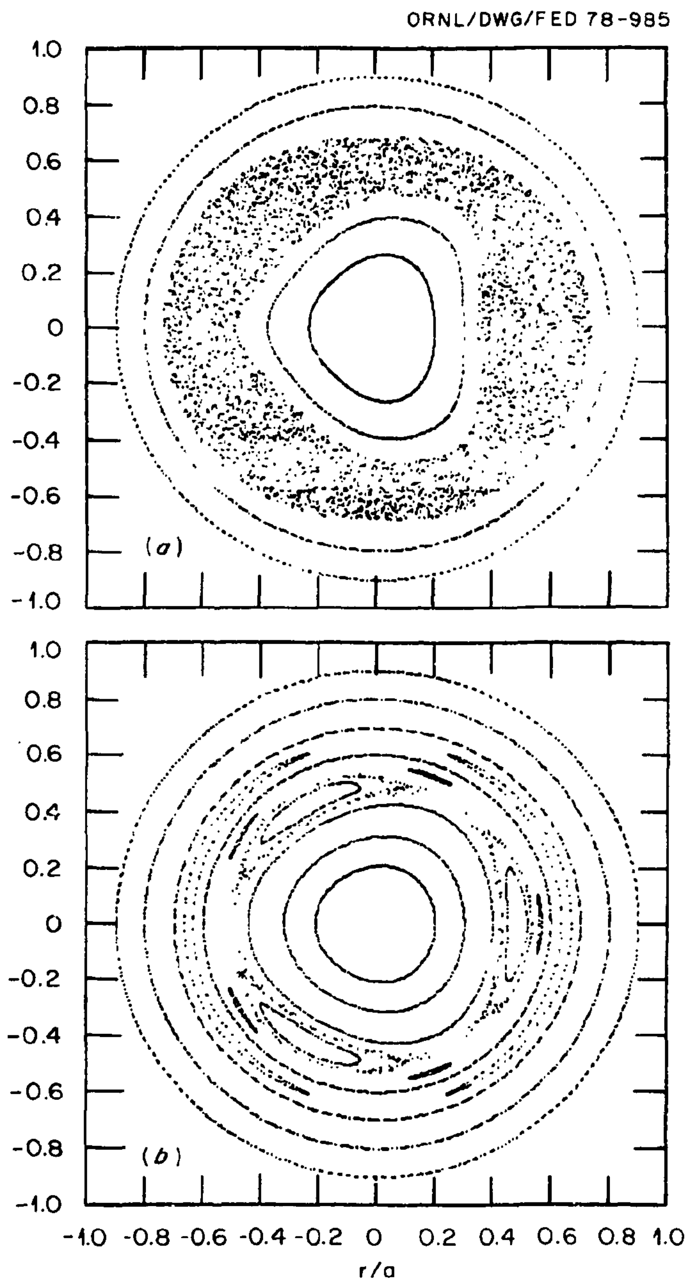

ORNL/DWG/FED 78-985
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
(a)
(b)
-1.0 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0
r/a

Fig. 10.

ORNL/DWG/FED-78-1151

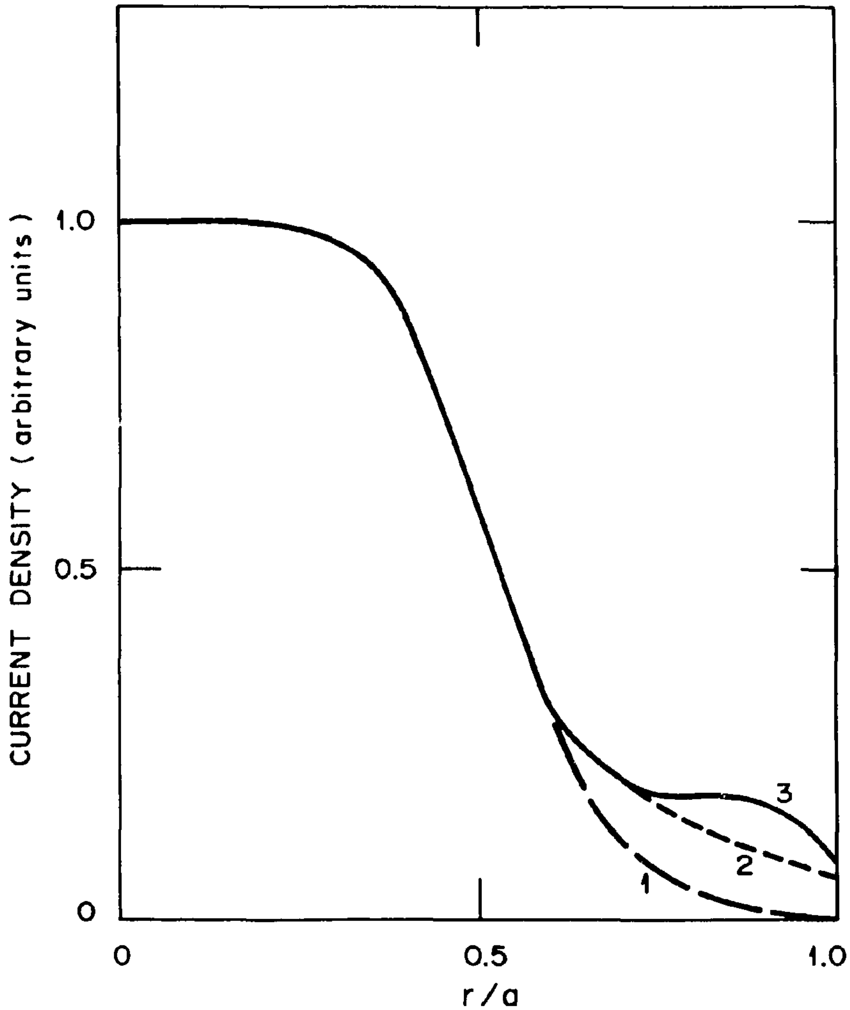


Fig. 11.

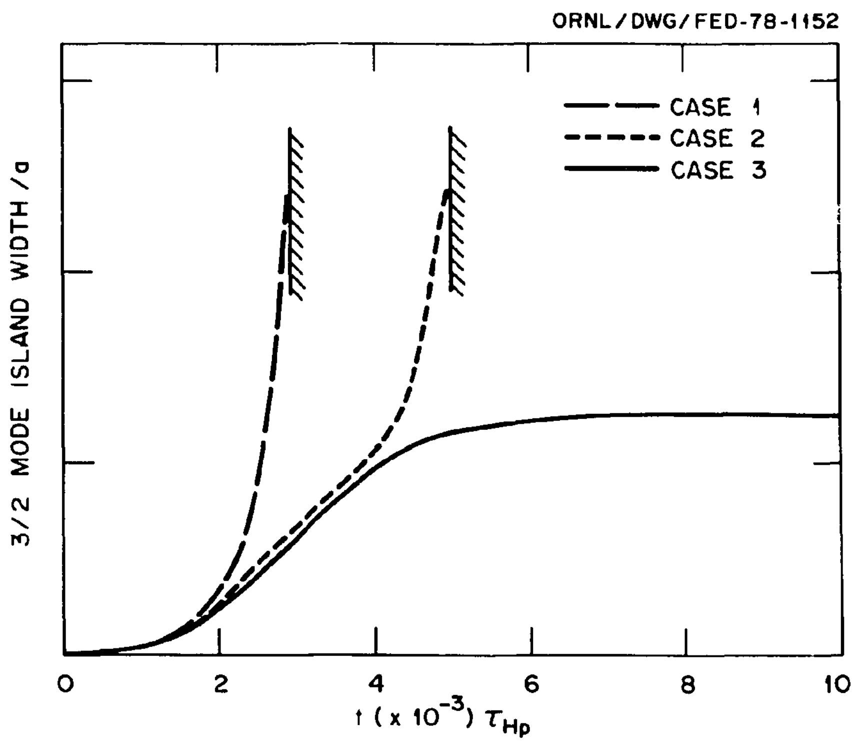

ORNL/DWG/FED-78-1152
CASE 1
CASE 2
CASE 3
3/2 MODE ISLAND WIDTH /a
0
2
4
6
8
10
t (x 10^-3) τHp

Fig. 12.

ORNL/DWG/FED 78-1265

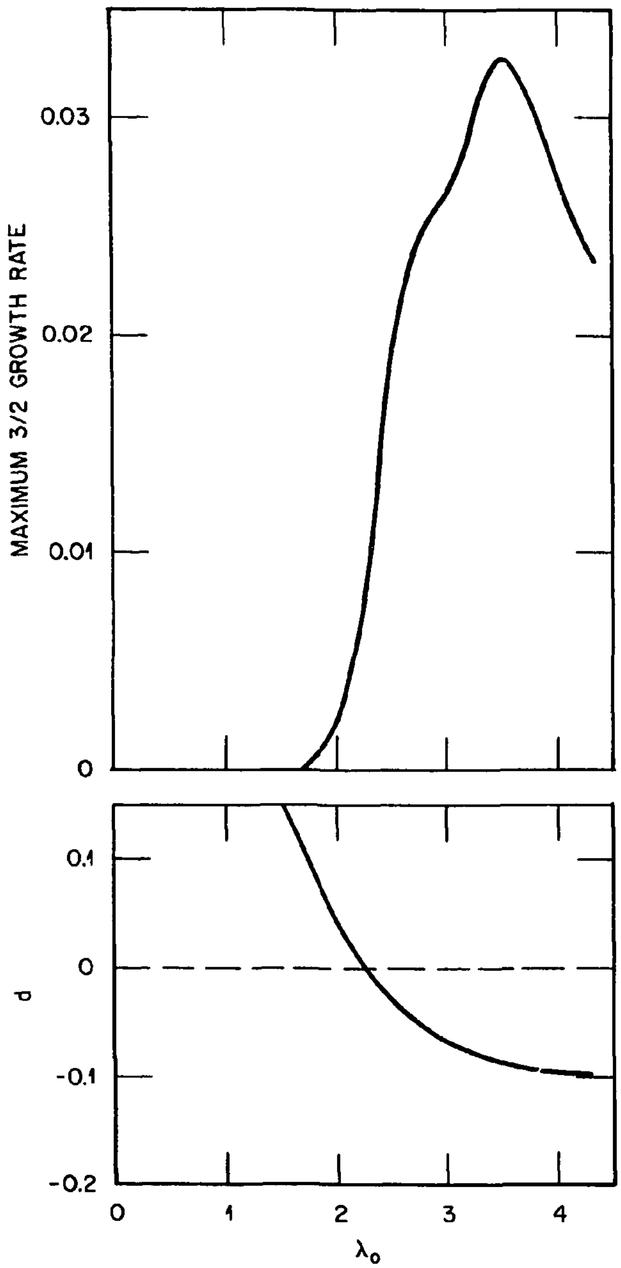


Fig. 13.

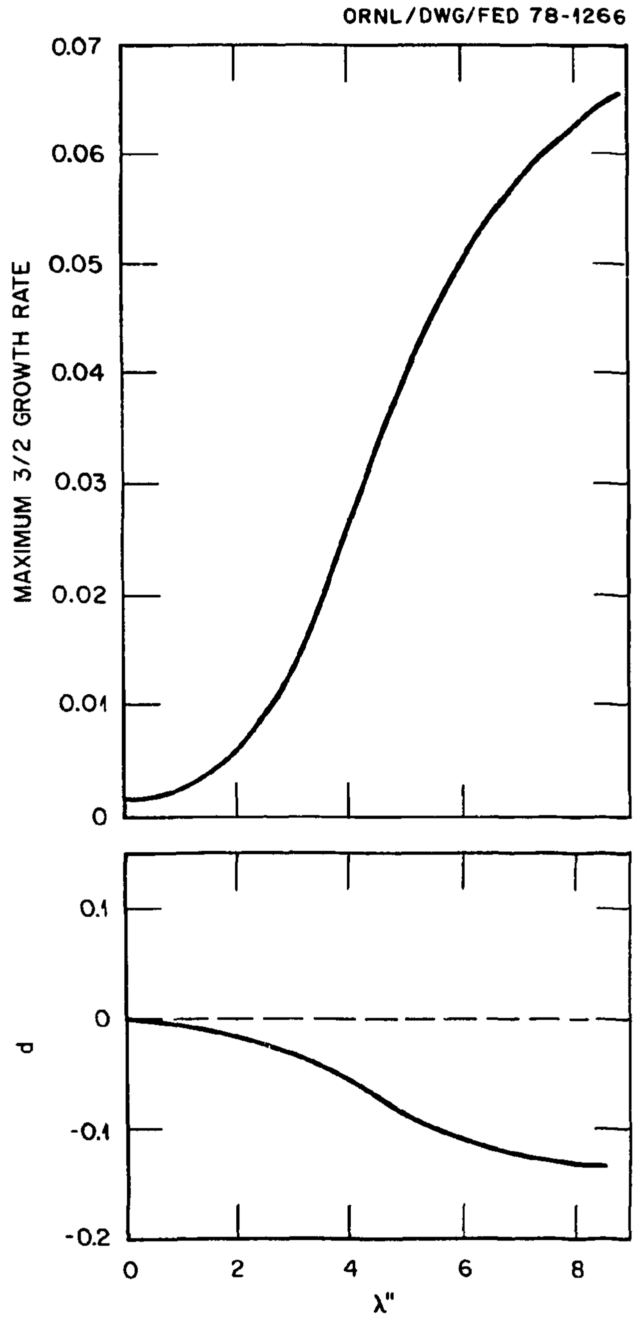

ORNL/DWG/FED 78-1266
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
MAXIMUM 3/2 GROWTH RATE
0.1
0
-0.1
-0.2
d
0
2
4
6
8
λ"

Fig. 14.

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