the entire minor circumference, it should be possible to use a limiter on only one-half of this circumference—in that part of the torus where the ion ∇B-drift direction is outward. Then most atoms removed from the limiter (by charge-exchange neutrals, runaway electrons, bulk plasma contact, etc.) should drift out, making no significant penetration. Bulk plasma interaction with the wall in the other half of the torus would remain negligible, since field lines near the wall there would still intersect the limiter at some point. Alternatively, even with a complete limiter, the plasma might be positioned above or below the midplane of the vacuum vessel by the programming of the external horizontal field coils. In this way, bulk plasma contact with the limiter in the appropriate portion of the torus would be minimized.

In conclusion, this Letter reports the first direct observation of the effects of ∇B-drift transport of impurity ions in tokamak geometries. The very general nature of the effect has been discussed. Finally, we stress its most important consequence—that in regimes of very high collisionality, impurity transport in tokamaks can no longer be considered one dimensional, but must be given a full two-dimensional treatment.

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Simulation of Large Magnetic Islands: A Possible Mechanism for a Major Tokamak Disruption

R. B. White, D. A. Monticello, and M. N. Rosenbluth[(a)]
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
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It is known that an internal tokamak disruption leads to a current profile which is flattened inside the surface when the safety factor equals unity. It is shown that such a profile can lead to $m = 2$ magnetic islands which grow to fill a substantial part of the tokamak cross section in a time consistent with the observation of a major disruption.

The involvement of the tearing mode in the major tokamak disruption has been suspected for some time.[1] We have developed a numerical method for examining the full nonlinear behavior of tearing modes of a single helicity.[2] The essential approximation in this analysis is the use of the tokamak ordering $B_z \gg B_\theta$ to expand the magnetohydrodynamic fluid equations to lowest order in the inverse aspect ratio. In this approximation modes of different helicities are uncoupled and the full nonlinear development of an initial perturbation consisting of a single helicity can be described in two dimensions.

Derivation of the reduced set of magnetohydrodynamic fluid equations is carried out in Ref. 2. Eliminating the unknown pressure by operating on the equation of motion with $\hat{z}\cdot\nabla x$, and keeping only lowest order in inverse aspect ratio, but including finite conductivity in Ohm's law, we find a closed set of equations. The resulting two-dimensional equations are, using the scaled variables of Ref. 2,

$$D\psi/Dt = -\eta J/S + E, \tag{1}$$

$$(D/Dt)\nabla(\rho\nabla A) = \hat{z}\cdot(\nabla\psi\times\nabla J) - \nabla\rho\times\nabla(v^2/2), \tag{2}$$

$$D\rho/Dt = 0, \tag{3}$$

$$J = -\nabla^2\psi - 2, \tag{4}$$

$$\hat{v} = -\vec{Z}\times\nabla A, \tag{5}$$

where ψ is the helical flux, D/Dt is the convective derivative, J is the toroidal current density, η is the resistivity, E is the electric field at the tokamak wall, ρ is the plasma density, and v is the plasma velocity. The parameter S equals τ_R/τ_A, where τ_R and τ_A are the resistive and poloidal Alfvén times, respectively. In present tokamak discharges $S\approx 10^7$ at the plasma center and decreases as $\eta^{-1}\rho^{-1/2}$.

Analysis of the results of a numerical code[3] which directly advanced Eqs. (1)–(5) has led us to the construction of an analytical model for the observed saturation of the mode at a relatively narrow island width.[4] When this saturation occurs, it can be understood quite simply. The tearing mode is driven by the difference in magnetic field energy between the initial state (no island) and the final state (an island of width w). This transition requires the tearing and reconnection of magnetic lines of force in a resistive layer near the mode rational surface and the growth rate is thus a hybrid between the magnetohydrodynamic and the resistive time scales. The essential feature of the saturation is that this magnetic driving energy decreases to zero as the island width increases; the way in which it does so is dependent on the amount of shear present in the equilibrium. Physically, an increased shear inhibits large island formation by making the island configuration less energetically favorable. In this Letter we use these analytic and code results to interpret experimental data concerning major tokamak disruptions.

Recent experimental measurements[5] of plasma x-ray emission during major disruptions observed in PLT have given some indication of the radial profiles of the plasma during these events. In particular, it was noted that the $q=2$ surface was at a radius larger than observed for stable discharges, and the temperature profile was abnormally flat. The disruptions were preceded by $m=1$ sawtoothing, possibly responsible for this flattening,[6] which abruptly ceased approximately 10 msec before the major disruption with the disruption itself initiating at the $q=2$ surface and propagating inward at a constant rate. During the final 10 msec preceding the onset of the disruption, there appeared growing $m=2$ precursor oscillations, sometimes accompanied by a weaker $m=1$ mode. The $m=1$ x-ray traces[5] do not possess a radial node, indicating the absence of a $q=1$ surface. The frequency of the precursor decreases as the perturbation grows.

Much of the experimental data can be understood in terms of our analytic and numerical results. In Fig. 1 are shown sample current profiles and safety-factor profiles for which we have analyzed the nonlinear behavior of $m=2$ tearing modes. The $q=2$ surfaces are located at $r=0.7$, the experimentally observed location, and the $q=1$ surfaces at $r=0.2$ (subscript a), nonexistent (subscript b), and $r=0.5$ (subscript c). J_b and J_c are the so-called flat current profiles,[7] $q(r)=c[1+(r/r_0)^8]^{1/4}$.

In Fig. 2 are shown the predictions from the saturation theory for these cases. Although for large widths this theory is only of qualitative use, note that as r_0, a measure of the current profile thickness, increases, the $m=2$ mode passes from linearly stable (curve w_c) to a small saturated island (curve w_a) to a large island (curve w_b). (Subscripts are as for Fig. 1.) As the $m=1$ sawtoothing has the effect of increasing the width of the current channel without changing the location

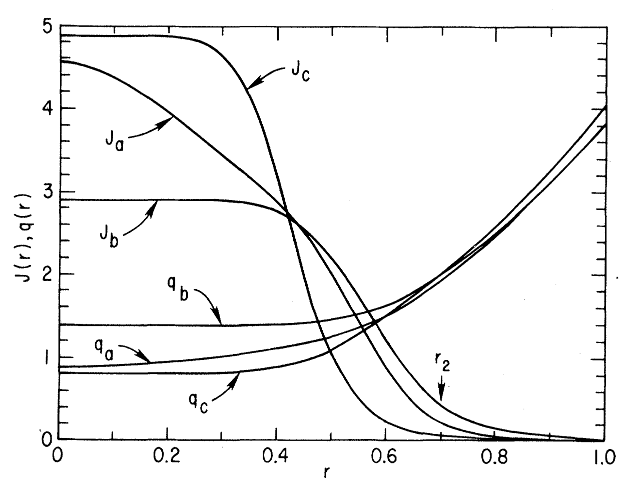

FIG. 1. Selected current profiles with $q=2$ surfaces at $r=0.7$. Also shown are the corresponding safety-factor profiles. The $q=1$ surface are at $r=0.2$ (subscript a), nonexistent (subscript b), and $r=0.5$ (subscript c). The current profiles J_b, J_c are the flat current profile of Ref. 7 with $r_0=0.6, 0.45$. q_a is obtained by modifying q_b for $r<r_1$.

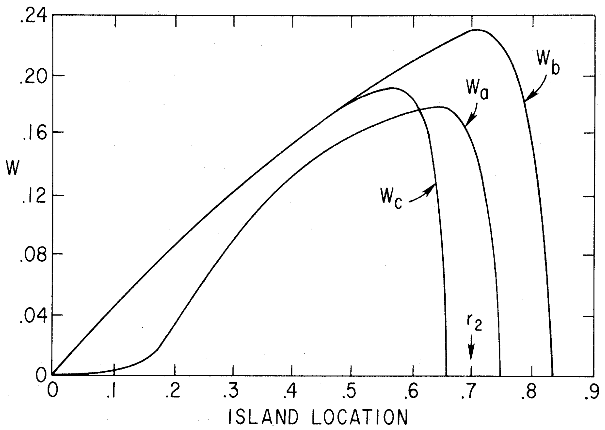

FIG. 2. Predicted satuaration widths for the profiles of Fig. 1. The $m=2$ mode for the $q=1$ surface at $r=0.5$ is linearly stable (curve w_c) and at $r=0.2$ it saturates at a fairly narrow island width.

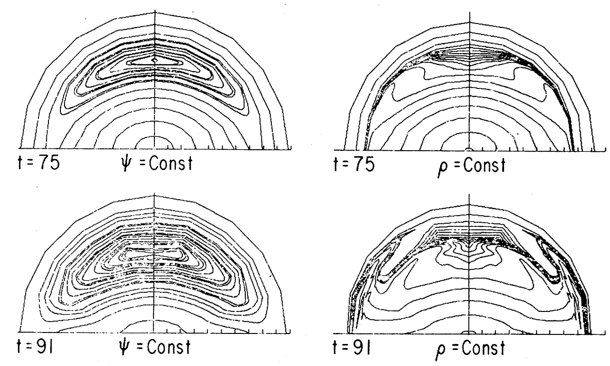

FIG. 3. Helical flux contours and density contours during the growth of a $m=2$ mode using the current profile J_b of Fig. 1. Here the resistivity is modeled as $\eta \sim 1/J$, $S=10^4$ at $r=r_2$. The units of time are the central Alfvén time τ_A.

of the $q=2$ surface, it would tend to produce this progression of states.

With the onset of the precursor oscillations the $m=1$ sawtoothing ceases and the $q=1$ surface vanishes; the experimental evidence for this being the vanishing of the nodal point in the $m=1$ mode. This is consistent with an increase of $q(0)$ to a value greater than 1, as shown by curve w_b. Numerically we observe, using a version of the code which also advances plasma temperature, that the presence of a $m=2$ island can increase radial thermal conductivity enough to cool the plasma and lower the central current density, hence increasing $q(0)$. Hence, we associate the onset of the precursor oscillations with the existence of a $m=2$ island of some critical size. As this thermal balance must include effects of Ohmic heating and radiation, an exact estimate of the width necessary is difficult to make, but we observe that an island of width $w=0.1$ increases $q(0)$ by approximately ten percent. This $m=2$ island would also drive a $m=1$ mode through toroidal coupling, and experimentally when the $m=1$ mode is observed it is in phase with the larger $m=2$ mode. We have examined mode rotation with a version of the code which includes finite-Larmor-radius effects through the addition of the Hall term to Ohn's law and including gyroviscous terms in the equation of motion. We find that the saturation results are not affected, but there is a nonlinear decrease in the frequency of the mode. This effect cannot be quantitatively correlated with the experimentally observed decrease in the frequency of the precursor at present because of the absence of measurements of island width.

At this point in the history of the discharge, the $m=2$ island would commence to grow rapidly, since a feedback mechanism exists whereby the island, through increasing radial conductivity, increases $q(0)$ and thus leads to a larger saturation width.

Once $q(0)$ has become larger than unity, the saturation theory suggests that large islands are possible, and we have investigated this case with our numerical code. In Fig. 3 are shown the helical flux contours and density contours for the case with subscript b of Figs. 1 and 2, a flattened profile with $r_0=0.6$, $r_2=0.7$, and $q(0)=1.37$. The final saturated width is $w=0.7$; this value being sensitive to the value of $q(0)$, a case with $q(0)=1.1$ saturating at $w=0.4$. Since the amount of computing time for a run is proportional to S, we have used a value of $S=10^4$ at the $q=2$ surface, which is lower than the experimental value. The resistivity is modeled as $\eta \sim 1/J$. The time is given in units of τ_A at the plasma center, which is less than 1 μsec for typical discharges. The mode is observed to continue exponential growth with no slowing down up to the final width shown, at which point it abruptly stops. We have also run a case with $S=10^5$ out to a width of $w=0.4$ to examine the scaling with temperature. In this case dw/dt becomes constant as described by Furth, Rutherford and Selberg[8] with $dw/dt \approx 30/\tau_R$ for $w>0.04$, where τ_R is to be evaluated at the $q=2$ surface. In the PLT disruptions, τ_R at $q=2$ is approximately 0.1 sec, and thus the Rutherford growth of the island is consistent with the growth of the precursor oscillations in a time of a few milliseconds agreeing with the experiments. The same sequence of events which we have sketched above also is observed in disruptions of TFR,[9] and the time of 1 to 2 msec for the growth of the precursor oscillations is again in agreement with the Rutherford growth time for a $m=2$ mode.

We have taken the plasma density to be a Gaussian function of r with $\rho(0)/\rho(r_2)\approx 10$, but the results are insensitive to the density profile. In Fig. 3 one notes, however, as the island reaches maximum size, the onset of a "vacuum" bubble, modified in shape from the results of Ref. 2 by the presence of shear and the imperfect vacuum-plasma boundary. This is consistent with an experimentally observed increase in the plasma radius in the last stages of the disruption, and could cause the plasma to make contact with the limiter.

The plasma disruption itself consists of a rapid loss of energy, perhaps due to both radiation and losses to the wall. An experimentally observed sudden increase in the density of tungsten throughout the plasma can be understood in terms of an island such as that shown in Fig. 3 making contact with the limiter. The experimentally observed 500-μsec time scale for the subsequent loss of energy and plasma is beyond the scope of the present model.

The boundary condition of constant electric field at the tokamak wall which we impose does not allow us to examine the question of the negative voltage spike observed toward the end of a major disruption. Moreover, as has been previously suggested,[10] this effect may be the result of the expanding plasma making contact with the limiter or wall.

We have repeated the same case with a version of the code which advances the plasma temperature and includes a more realistic model for the resistivity through $\eta=T^{-3/2}$. Again we find essentially the same growth and final width.

A number of effects may contribute to the major disruptions seen in tokamaks in addition to those which we are able to treat in our code, which is limited to a single helicity. Nonlinear coupling between modes may be important and can lead to large regions of ergodic field lines, as can toroidal effects acting on a single large island. The nonlinear coupling could possibly produce the 500-μsec time scale.

In this Letter, we show that when the current profile internal to $q=1$ is very flat and is consequently very steep in the neighborhood of $q=2$, the $q=2$ island evolves to a very large size. This is a more general phenomenon in the sense that a profile with large flattening at $q=1$ and $q=2$ would be violently unstable at $q=\frac{3}{2}$, etc. Hence, one might expect that in the final stages of shrinking, flattening, and disruption many modes would be involved.

Nonetheless, we have shown that, for a flattened profile similar to the one observed before the onset of the precursor oscillations, a relatively small evolution of the zeroth-order profile is enough to change the $m=2$ mode from a condition of small amplitude saturation to the "disruptive" case. Furthermore, the necessary zeroth-order change in the profile is understood qualitatively as being due to increased radial conductivity. Such a large island would almost certainly initiate a drastic loss of confinement were such factors as ergodicity and interaction with the limiter taken into account. Although the model we propose is incomplete and probably not universal (a flat current profile possibly can be obtained through other means than sawtoothing, and there may be several types of major disruption) it appears to be a sufficient disruptive mechanism consistent with present experimental evidence.

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