MARYLAND CONTROLLED FUSION RESEARCH PROGRAM

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I. INTRODUCTION

Purpose: The Maryland Theory Program is dedicated to the following tasks:

- (i) To intensify our effort to develop an understanding of the fundamental processes which produce anomalous transport in tokamaks and to propose methods for enhancing confinement.
- (ii) To continue our investigation of tokamak edge plasma turbulence, sheared flow generation and the L/H transition.
- (iii) To continue our investigation of major disruptions with an emphasis on developing techniques for stabilization.
- (iv) To continue collaborations with experimentalists and theorists of major fusion laboratories and university fusion centers for close interplay of theory, experiment, and simulation.
- (v) To provide the theoretical support to the existing and proposed Maryland experimental programs in plasma diagnostics such as laser particle tagging and cyclotron radiation measurements from tokamaks.
- (vi) To continue the education and training of scientists in plasma theory relevant to fusion.

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II. TECHNICAL PROGRESS

In the past three years, members of the Maryland Plasma Theory Group have made significant contributions to the national fusion theory program, and, in many cases, these theoretical developments helped to interpret experimental results and to design new experimental programs.

In the following, we summarize the technical progress in four major areas of tokamak research: (a) L/H transition and edge turbulence and transport; (b) active control of micro-turbulence and transport; (c) major disruptions; and (d) the sawtooth crash.

A. L/H Transition and Edge Turbulence and Transport in Tokamaks

The measurements of improved energy confinement during the L/H transition in tokamaks as a result of the formation of an edge transport barrier has had a dramatic impact on research in anomalous transport. While the improvement in confinement was itself important, perhaps more significant was the realization that anomalous transport can be mitigated. The recent observations of internal transport barriers in DIII-D, JT-60 and PBX-M reinforce this optimistic viewpoint. Thus, the development of a first principles theoretical model of the transition is crucially important and has been one of the primary goals of the Maryland Fusion Theory effort.

The development of such a model requires first an understanding of the source of fluctuations and associated transport in the tokamak edge. Measurements of fluctuations in CCT demonstrate that the fluctuations balloon towards the outside of the machine. The inboard/outboard asymmetry of the heat flux on the divertor plates of other machines is consistent with the anomalous transport rate being peaked on the outside of the machine. Thus, curvature must play a role in the growth of edge turbulence. Recent experimental measurements at UCLA and on DIII-D at GA have shown that poloidal rotation very likely plays an important role in the onset of the H-mode. Measurements on TEXT indicate that sheared rotation has a stabilizing influence on edge turbulence and locally reduces transport. Thus, the second requirement for explaining the L/H transition is to understand both the generation of poloidal rotation and its feedback on the turbulence. Our group has played a lead role in both of these areas.

A few years ago, we developed a conceptual model of the tokamak edge in both L- and H-mode.^{1,2} In this model we identified three important ingredients: poloidally asymmetric transport driven by the drift-resistive ballooning mode,^{3,4} parallel flows of the order of the sound velocity (c_s) produced by the asymmetric transport,^{5,6} and poloidal rotation (Stringer mechanism) produced by these parallel flows^{1,3}. The non-

linear interaction between these three components determines whether the plasma remains in L-mode or makes a transition to the H-mode. When magnetic pumping is large, the poloidal rotation remains of the order of the diamagnetic level. Poloidally asymmetric transport produces a significant variation of the density along flux surfaces in the edge and results in parallel flows of order c_s . Experimentalists on CCT, TEXT and DIII-D are presently attempting to confirm the presence of these parallel flows in L mode edge plasmas. When the magnetic pumping is weak, the Stringer mechanism (parallel flow) causes the edge plasma to spin, amplifying the existing diamagnetic level shear layer which is present in the L-mode. Poloidal rotation increases to $V_\theta \sim c_s a / qR$ when poloidal rotation competes with the parallel flow in smoothing the edge poloidal asymmetries. In the H phase the poloidal asymmetries and consequently parallel flows are greatly reduced. Transport is suppressed by sheared rotation, allowing steepened edge density gradients. This model remains a plausible candidate to explain the L/H transition. Two new ingredients, however, must now be added to this picture. First, we now know that even in the absence of rotation, edge turbulence can be stabilized by the diamagnetic drifts of ions and electrons and that this is an important effect at the L/H transition⁷. Secondly, the ion pressure gradient can drive rotation⁸.

In the following sections we describe the more detailed calculations we have completed and are presently pursuing to understand tokamak edge turbulence and develop a first principles model of the L/H transition. Our work² was highlighted as an important new theoretical model of the L/H transition in the 1992 IAEA summary talk by Dr. Pogutse. Two invited talks were presented at the 1992 APS meeting on this work. At the 1994 IAEA meeting our paper⁷ was the only theoretical post-deadline paper selected for oral presentation.

1. 3D Fluid Simulation of the Nonlinear Drift Resistive Ballooning Modes in Tokamak Edge Plasmas

The single most important experimental observation for identifying the cause of fluctuations and transport in tokamak edge plasmas is the strong inside-outside asymmetry of the anomalous particle flux (with a larger flux on the outside). This indicates that an instability with an outward ballooning character would be the most likely candidate for driving the observed particle flux. Since most edge plasmas are collisional, the only model which has the necessary requisites is the drift resistive ballooning mode (DRBM).³ Thus over the last two years we have studied the nonlinear behavior of DRBM turbulence, transport and the self-consistent generation of flows.⁴ This work first required a careful analytic analysis of the dominant scale lengths and time scales and second the development of a novel numerical algorithm for advancing the Braginskii fluid equations in toroidal geometry. At this point in time our computer code used to evolve the nonlinear Braginskii fluid equations has evolved through several generations. Our priority has always been able to complete simulations with real parameters in a torus and we were the first group to do this. Our fundamental assumption, based on observations is that the poloidal correlation lengths of edge

turbulence are short while parallel correlation lengths are long. In our first model we advanced the equations on a helical coordinate system based on a low order rational surface in the edge⁴. The variation of curvature with position along B was readily evaluated. Hard wall boundary conditions, however, caused local flattening, reducing fluctuations and transport. Our latest code⁷ uses flux-based coordinates with periodic boundary conditions radially and implicit treatment of the parallel dynamics. Now included are the full dynamics of electrons and ions with T_e and T_i taken to be constant. We now regularly complete fully resolved 3-D simulations to saturation with modest usage of computer time.

An important result is that the nature of edge turbulence is basically controlled by a single diamagnetic parameter α ^{4,7}. For $\alpha < 1$, which is representative of Ohmic and L-mode plasmas, we have shown that:

- (i) The fluctuations are large ranging from 10-50%, depending on parameters with $D_{\perp} > 10^4 \text{ cm}^2/\text{s}$.
- (ii) The turbulence and transport has a strong ballooning character.
- (iii) The radial and poloidal correlation lengths were found to be in reasonable agreement with observations on TEXT⁹.
- (iv) The generated sheared flows due to Reynolds stress¹⁰⁻¹² alter the transport rates by factors of two but do not stabilize the turbulence.

For $\alpha > 1$, which corresponds to H mode we have shown that:^{7,13}

- (i) The magnetic curvature plays no role in driving the turbulence.
- (ii) The turbulence self-sustains even though there is no linear instability.
- (iii) The turbulence is driven by a nonlinear streaming instability in which radial flows produce poloidal density gradients. These gradients drive drift-waves (even with magnetic shear) which in turn amplify the radial flows.
- (iv) When the ion Larmor radius exceeds a critical value the nonlinear instability is quenched and the turbulence dies away.

A simple truncated mode model of the nonlinear instability has been constructed which illustrates that the instability mechanism appears generic, i.e., it seems likely that this basic phenomenon may also occur in the core of the discharge. This example of the fundamental failure of linear theory to describe the nonlinear state of the system has significant ramifications beyond the fusion program.

2. Formation of the Shear Layer and the Development of Parallel Flows in Toroidal Edge Plasma

Experimental measurements on TEXT and other tokamaks and stellarators indicate that a shear layer (region of sheared poloidal rotation) forms near the boundary between open and closed flux surfaces in the tokamak edge. This shear layer is present in Ohmic plasmas and the enhancement of this layer during the L/H transition leads to shear stabilization of edge turbulence and improved confinement in the H-mode. Thus, the development of a theoretical model of the shear layer is an important goal of the theory program.

The development of parallel and perpendicular flows in toroidal edge plasma has been investigated in the presence of an anomalous ballooning-like transport.⁶ The model is based on the Braginskii fluid-equations in an axisymmetric torus. A priority of this work has been to properly model the *transition between open and closed field lines* where the shear layer forms. Key results of this work are as follows:

i. The equilibrium density evolves so that the transport rate $D_{\perp}/L_n^2$ equals the sound rate, $c_s/\pi q R$. Since diffusion and sound rates are comparable, the variation of the density along a flux surface in the edge is of order unity and parallel flows of order c_s are generally expected. This result also implies that confinement is linked to the parallel dynamics.

ii. In the open flux region the radial electric field is outward as a result of the Bohm sheath at the limiter or divertor plates. The poloidal rotation rate is at the diamagnetic level.

iii. When magnetic pumping is large the rotation in the closed flux region is equal in magnitude and opposite in direction to the ion diamagnetic drift (inward radial electric field), the usual neoclassical result.

iv. When magnetic pumping is weak, poloidal rotation in the closed flux region is amplified by the Stringer mechanism (with inward electric field) to a level close to the poloidal sound speed (ac_s/qR).

3. Linear Theory of Drift Resistive Ballooning Modes: A New Unstable Branch

Over the last two years we have re-examined the stability of drift resistive ballooning modes for the edge region of tokamaks¹⁴. This work was motivated by results from our 3D code work, which showed that for realistic shear ($\hat{s} \sim 0(1)$), the mode was robustly unstable and strongly ballooning. The conventional theory for these modes shows that the mode is weakly ballooning and not so unstable as found in our 3D work. To reconcile the difference between existing theories and our numerical results we re-examined the stability theory for these modes. We have found analytically that a) for $\hat{s} \ll 1$, there are basically two unstable branches of the resistive

ballooning mode. The 'conventional' branch³ is the more unstable branch of the two. Both branches were weakly ballooning. b) By tracing the two branches from $\hat{s} \ll 1$, to $\hat{s} \sim 0(1)$, we found that the conventional branch became strongly stabilized, while the new unstable branch became robustly unstable. Also the eigenfunction for the conventional branch remained weakly ballooning for finite shear. On the other hand the new unstable branch became more strongly ballooning. Both the growth rates and the eigenfunction for the new branch are consistent with our 3D results and further reinforces our contention that these modes are a prime candidate for causing anomalous transport in the edge region of tokamaks.

3b. Resistive Ballooning Modes in the Scrape-off-Layer of Tokamak Plasmas

Analytical and numerical studies of the stability of the Resistive Ballooning Modes in the scrape-off-layer of a tokamak plasma has been studied¹⁵. The important question is what is the role of the sheath boundary condition on stability of resistive ballooning modes. We find that the stability of the RBM is controlled by two parameters, $\lambda = (m_e/m_i)^{1/2} \nu_{ei} Rq / v_{Te}$, the "effective strength" of the Debye sheath current, and $\hat{m} = mL_0/a$, the dimensionless poloidal mode number, where L_0 is the characteristic scale of the resistive modes as defined in our earlier work^{4,7,14}. High mode number modes $\hat{m} \gg 1$ are always strongly ballooning and decouple from sheath. The stability of low mode number modes depends on λ . For $\lambda \ll 1$, which is characteristic of most present day tokamaks, the low mode numbers are unstable. However for $\lambda \gg 1$ (projected value for ITER), the modes with $\hat{m} \leq 1$ are strongly stabilized. Both these limits ($\lambda \ll 1$ and $\lambda \gg 1$) are amenable to an analytical treatment. For $\lambda \sim 0(1)$, we have studied the stability numerically. The influence of diamagnetic effects has also been investigated.

4. Stringer Spinup in the Banana Regime

We have proposed the Stringer mechanism as a possible explanation for the spontaneous spinup at the tokamak edge leading to the H-mode. The underlying theory was done in the Pfirsch-Schlüter limit. In tokamak such as DIII-D, the collisionality parameter at the edge is of order unity. Thus, it is important to know if the Stringer mechanism applies in other neoclassical collisionality regimes. We have completed a theory of the Stringer spinup¹⁶ in the banana regime. With minor modifications, we obtain essentially a similar spinup instability as that in the Pfirsch-Schlüter regime. One modification has to do with effective inertia. In the banana regime, trapped ions process toroidally in response to a radial E field much more rapidly than the $E \times B$ drift speed itself. This makes for a larger effective inertia than the usual $1 + 2q^2$ of the PS regime. The enhancement, reported elsewhere in this report, is of order $\epsilon^{-1/2}$.

The enhancement of the effective mass is also important for schemes for driving poloidal rotation by external momentum input. It would mean that the poloidal rotation would take longer to build up than the ion temperature or the density buildup.

This concern is of importance because one would want the density to stay low in the early stages so as to attain a high rotation speed and affect the discharge before the density builds up. Fortunately, a factor of $\epsilon^{-1/2}$ is small enough not to be prohibitive.

5. The $V_{||}'$ Instability in Tokamak Edge Plasma

Our first 3D simulations of DRBM⁴ have succeeded in explaining many aspects of experimental observations of edge turbulence as discussed earlier. Recently large-scale, axisymmetric vortices have been measured in the edge of CCT. These low mode number vortices can not be curvature-driven at the low values of β in these experiments. Localized parallel flows are unstable to an electrostatic instability which transports momentum across B, the $v_{||}'$ instability, which may produce these vortices. The ballooning character of the transport leads to the development of radially localized parallel flows $v_{||}$ from the outside to the inside of the machine^{5,6}. These flows are of the order of c_s and can also drive turbulence.

Two investigations of the $V_{||}'$ instability have been pursued. In the first, we explored the instability of a toroidal plasma to axisymmetric vortices driven by $v_{||}'$ to explain the recent observations on CCT.¹⁷ We demonstrated that axisymmetric vortices evolve to large amplitude if $\rho_s q R / a L_n > 1$. In CCT because of the weak magnetic field this inequality is satisfied and such vortices are expected while in most other tokamaks the inequality is not satisfied and only nonaxisymmetric disturbances are unstable.

In the second investigation we have developed a fully nonlinear 3 dimensional code to study the nonlinear turbulence and transport of the $v_{||}'$ instability.¹⁸ We use a field aligned coordinate system with a sheared magnetic field. The equations that we evolve are the ion continuity equation and the parallel momentum equation. The perpendicular dynamics of the ions are due to the $E \times B$ drift and the polarization drift, and the electrons are presumed to respond adiabatically. We drive a background parallel velocity profile with radial gradients that mimic the flow pattern of the edge.

In dimensionless form, the equations contain three parameters, $\alpha = 2\pi q R \rho_s / L_v^2$ which is a ratio of the growth time to the parallel sound transit time, $\hat{\rho} = \rho_s / L_v$ which determines the strength of the polarization drift, and $\hat{s} = d \ln q / d \ln n$ which is a measure of the magnetic field shear. For the edge, $\alpha \gg 1$, $\hat{\rho} \ll 1$, and $\hat{s} \sim 1$. We examined the dependence of the turbulence and the transport on these parameters. Our most important result is that this instability drives large fluctuation levels (30% - 50%) and gives transport rates of the order $\sim \rho_s c_s$. The perpendicular scale length of the turbulence in both the x and y directions is of the order of the scale length of the velocity gradient. The parallel structure is determined by the parameter α . As α increases, so does the number of wavelengths along the field, however, the perpendicular mode structure remains fairly unaffected. In agreement with this, the saturated transport rate also seems to be independent of α . The value of ρ has little effect on the saturated transport rate, however, it does play a critical role in

initiating vortex mixing at the earlier nonlinear stages. The impact of magnetic shear is presently being explored. Preliminary indications are that magnetic shear is too weak to cause radial localization of the turbulence.

6. Disintegration of Ion Banana Orbits in Tokamak Edge Plasmas

Ion orbit loss is a mechanism believed to be responsible for the radial electric field observed in the edge region of tokamaks¹⁹. However most of the calculations that determine the ion orbit assume that the plasma in the edge region is quiescent. However it is well known that the edge has large density and potential fluctuations. Therefore we have investigated the orbits of the electrons and ions in a toroidal plasma in the presence of low frequency fluctuations. We have found that at fluctuation levels well below those observed experimentally, the ion banana orbits are significantly modified by the fluctuations²⁰. This modification leads to a strong reduction in the momentum imparted to the plasma by orbit loss. Thus the present work suggests that the ion orbit loss may not be a viable mechanism for driving poloidal rotation at the L-H transition in tokamaks.

B. Active Control of Micro-turbulence and Transport

There is strong experimental evidence that perpendicular velocity shear may suppress micro-turbulence. In the past several years we have been in the forefront of research identifying mechanisms by which a plasma may be externally torqued to set up sufficient velocity shear to improve confinement.^{6,21-23} Our focus has been broad, examining ways to drive rotation and suppress turbulence both in the edge and in the interior of the discharge. We have focused on two approaches to generate sheared flows: with neutral beams and with localized particle sources.

1. Neutral Beam Driven Rotation

We have suggested that NBI could be used to drive velocity shears.^{2,21-22} We have examined both poloidal injection and toroidal injection. In both cases, while the early calculations show that achievement of the above criterion will not be an easy matter, they also show that the proposed schemes are in the realm of feasibility. For poloidal injection, it may be possible to achieve a relatively narrow shear layer ($\lesssim 20\%$ of minor radius) with existing NBI injected poloidally. In toroidal injection, if the toroidal rotation speed can be made to exceed the sound speed, stabilization can be achieved.

An experiment to drive poloidal rotation on DIII-D, by off-axis NBI was proposed by us and run last year. Preliminary analysis shows an increase in stored energy relative to the on-axis "control" experiment. There is also evidence of a toroidal

rotation "pinch". Further data analysis and corroboration by theory is in progress.

2. Spin-up from Non-Axisymmetric Particle Fueling

If a source of plasma is turned on in a tokamak, with a source rate larger on the outboard side of a flux surface than on the inboard side, a spontaneous poloidal spin-up of the plasma can occur. We have recently demonstrated this¹⁶ in a calculation for an arbitrarily shaped, axisymmetric tokamak plasma where the particle (and momentum) sources may be nonaxisymmetric. Our calculation thus applies to particle sources arising from pellets, gas puffing, or centrally neutral beam fueled systems like TFTR supershots. The mechanism for the spin-up is the Stringer mechanism. The spin-up is destabilized provided the poloidally asymmetric portion of the particle fueling rate exceeds the damping rate of poloidal rotation from magnetic pumping reduced by a factor ϵ , the inverse aspect ratio.

In the edge plasma the optimum location of the source for driving poloidal rotation is not on the outboard edge of the plasma but on either the top or bottom depending on the direction of the toroidal magnetic field.⁶ The optimum location is on the side towards which ions are drifting in the toroidal magnetic field. A source at this location enhances the naturally occurring Stringer-drive of poloidal rotation in the edge. To the extent that the divertor throat acts as a source of neutrals these results are consistent with the experimental observation that the power threshold for transition to the H-mode is a minimum when the divertor throat is towards the direction of the ion drift. Exploration of the optimum location of particle sources for driving rotation is continuing.

This work was presented at the 1992 IAEA meeting.²

C. Major Disruptions

Major disruptions are an important limitation on the operating range of future large tokamaks such as ITER. The sudden loss of confinement during disruptions can cause severe damage to tokamaks. Therefore, it is important that disruptions are avoided during operation or, at least, that their damaging effects on the tokamak are ameliorated. We have previously simulated major disruptions in cylindrical geometry with a circular cross section using a reduced MHD Fourier code in which the reduced MHD variables are expanded in Fourier harmonics in the toroidal and poloidal angles.²³ Key features of our simulations of major disruptions were confirmed in experiments on the TFTR tokamak.²⁵ In particular, the initial loss of central confinement in the simulations is caused by the injection of a cold $m = 1$ plasma bubble from the edge of the discharge to the center. Subsequently, experimental investigations of disruptions on TFTR have shown that the loss of confinement begins with

the movement of a cold plasma bubble from the edge into the center, as predicted by our simulations.

In our recent work on disruptions we have continued to pursue an understanding of the underlying cause of disruptions by developing a new toroidal MHD code for exploring disruptions in a finite-aspect-ratio torus. At the same time we have explored some new techniques for suppressing disruptions by stabilizing the tearing mode.

1. Stabilization of the Tearing Mode by Overlap with Driven Alfvén Resonant Islands

The stability of the tearing mode in the presence of driven Alfvén waves has been studied numerically.²⁶ The model is reduced resistive MHD in a sheared slab with a driving electric field to produce a resistive equilibrium with a peaked current density. The traveling Alfvén waves are driven at a frequency such that the Alfvén resonance is near the region of large current gradient. The temporal evolution is studied as a function of the driving frequency and amplitude. The results indicate that the tearing mode can be completely stabilized. Stabilization occurs when the Alfvén resonance islands overlap the current layer, and is due to a combination of factors. The first is quasilinear flattening of the current profile. The second factor is that Alfvén waves at large amplitude in a sheared magnetic field have shear flow in their direction of propagation. This shear causes the tearing modes to propagate and saturate at a lower level. Therefore, at sufficiently large Alfvén wave amplitude, the tearing mode is damped. The quasilinear flattening is due to *self-consistent* "magnetic field line" chaos, i.e., chaos in the characteristics of $dx/dt = \pm v_A$. These results suggest that it may be possible to stabilize tearing modes in a tokamak by exciting low frequency Alfvén waves of the same helicity. Specifically, it may be possible to prevent disruptions (either density limit or current limit) by exciting $m = 2, n = 1$ Alfvén waves at a frequency such that the inner Alfvén resonance is at the radius of maximum current gradient, which appears to be just inside the $q = 2$ surface. Since the $q = 2$ surface is near the edge, coupling to the kinetic Alfvén wave should not occur. It is envisioned that the Alfvén waves be launched in response to disruption precursors allowing the density and/or current to be decreased on a slower time scale. This work was given in an oral presentation at the 1993 Sherwood meeting.

2. Toroidal MHD Code with Noncircular Cross Section

We have recently written a fully nonlinear toroidal MHD code. In this code, the nonlinear equations for the magnetic field, momenta, thermal energy, and density are solved on a three-dimensional spatial grid. Spatial derivatives are evaluated to fourth order on the grid while time stepping is second order accurate with a leapfrog trapezoidal scheme. Grid oscillations resulting from convection are stabilized with a

grid scale hyperviscosity. Since the code is fully explicit, it is particularly well suited for parallel processing. This fully gridded code is more suitable than Fourier codes for fully nonlinear three-dimensional simulations because a gridded code can more accurately resolve the steep gradients which arise nonlinearly. In Fourier codes, truncation of the spectrum gives rise to spurious ringing from steep gradients. We have tested our compressible MHD code on a model problem of the magnetic reconnection of two flux bundles. The results generated by our new compressible MHD code are essentially identical to those generated by our old reduced MHD code.

3. MHD Code; Stability of High-Beta Tokamaks

Our new toroidal MHD code has been used to study high beta tokamak equilibria with $\epsilon\beta_p \gg 1$, where β_p is the ratio of the plasma pressure to the poloidal magnetic field pressure and ϵ is the inverse aspect ratio²⁷. Previous efforts to study such equilibria have not been successful because of convergence problems associated with the poloidal structure. Our gridded code can readily resolve such structure. A two-dimensional version of the code which is symmetric in toroidal angle is used to calculate the equilibrium at high $\epsilon\beta_p$. The stability of these high $\epsilon\beta_p$ equilibria to low n kink modes has been evaluated, where n is the toroidal mode number. First results show that as the plasma beta in the equilibrium is increased, low n kink modes become more unstable with a larger growth rate. At low $\epsilon\beta_p < 1$, the growing $n = 1$ mode has an $m = 2$ structure in the poloidal plane, where m is the poloidal mode number. At high $\epsilon\beta_p > 1$, the growth rate of the $n = 1$ mode is much larger and the poloidal structure contains many poloidal mode numbers. The increase in the growth rate appears to be caused by the steeper current gradients formed in high beta equilibria.

D. Sawteeth in High Temperature Toroidal Plasmas

The dynamics of the central region of high temperature tokamak plasmas is frequently dominated by the so-called sawtooth oscillations giving rise to a more or less periodic redistribution of the energy in the region. The trigger of these relaxations is the internal $n = 1$ kink mode, where n is the mode number for variation of quantities in the toroidal direction. This mode corresponds to a nearly rigid shift of the internal region of the plasma. Its suppression or control is considered to be important in present and future tokamaks. In recent years two observational facts associated with sawteeth have remained serious puzzles. First, although the sawtooth crash, within experimental uncertainties, appears Kadomtsev-like it is now widely accepted that the central value of q is unchanged before and after the crash, in contradiction with the Kadomtsev model. Second, saturated $m = n = 1$ magnetic islands are often observed on TFTR while toroidal calculations based on resistive MHD indicate that these islands never saturate. We have presented detailed theories which explain both of these

observations. In addition we have explored both the linear stability of the $n = 1$ kink mode in the presence of trapped particles in a torus and the rate of reconnection in high temperature tokamaks where the MHD description fails.

1. Nonlinear ω_* -Stabilization of the $m = 1$ Mode in Tokamaks

The ability of MHD theory to predict the onset of sawtooth oscillations in tokamaks has been seriously challenged by the behavior of high-performance, TFTR plasmas: in sawtooth free discharges, the q -value on axis is often measured to be below unity²⁸, yet MHD stability codes predict the $m = n = 1$ mode to be unstable²⁹⁻³². The explanation of this "anomalous stability" is vitally important for a realistic assessment of tokamak performance in advanced devices such as ITER, and was the main goal of the present work^{32,33}. This work has led to a new concept of nonlinear sawtooth stabilization in tokamaks.

In the analyses of Refs. [31,32], an important clue was recognized: although the contradiction between linear theory and experiment persists when the stabilizing effects of the diamagnetic drift (ω_*) frequencies are included in the theoretical model, data analysis shows that the sawteeth in TFTR are nevertheless consistently suppressed when ω_* exceeds a certain critical level. This threshold, which cannot not be explained in the context of presently known linear theories, was proposed to arise from nonlinear effects³².

To assess this proposal, the nonlinear evolution of the mode was analyzed using numerical simulations of a two-fluid model³³. Although this model was simplified to demonstrate the main effects, physically realistic parameters, corresponding to the nearly collisionless, high temperature regimes of TFTR, were simulated. This was made possible by the development of a completely new approach that simulates the reconnection layer and island only. The solution in the external regions, valid in the early nonlinear stage, was obtained analytically and represented by an appropriate boundary condition. As claimed in Ref. [32], and in qualitative agreement with $m = 1$ behavior in TFTR, we found the unstable mode indeed saturates nonlinearly at a small amplitude provided the ion and electron drift-frequencies ω_* are sufficiently large. The main stabilizing effects are localized, nonlinear enhancements of ω_* and the magnetic shear q' near the $q = 1$ surface. The simulation results, e.g., the nonlinear stability threshold and saturation amplitude, were also shown to be reasonably well reproduced by quasilinear theory. At the quantitative level, however, the comparison to TFTR data suggests that additional stabilizing effects outside the present model are also important. A good candidate for such effect is the contribution of trapped (thermal and energetic) particles, the account of which is in progress.

2. Rapid Reconnection Driven by Electron Thermal Streaming in High Temperature Plasmas

It is widely believed that the crash phase of the sawtooth is a consequence of the reconnection of magnetic field lines. In classical Sweet-Parker resistive MHD theory,

the rate at which magnetic field lines reconnect is proportional to the square root of the Spitzer resistivity. However, the classical rate of reconnection based on Spitzer resistivity is far too small to account for the rapid phenomena observed during the crash of a sawtooth. For example, the time scale for classical magnetic field line reconnection based on the central temperature in the JET tokamak is more than ten times longer than the observed time scale for the drop in the central temperature during the sawtooth crash.

This apparent discrepancy between classical reconnection theory and experiment has motivated us to examine the effect of electron thermal streaming on the reconnection process. Electron thermal streaming can be included in the MHD equations by retaining the electron pressure in Ohm's law. We have carried out a series of reduced MHD simulations of the magnetic reconnection of two flux bundles using an Ohm's law which includes the parallel (to the magnetic field) electron pressure gradient.³⁴ We have found that the thermal streaming of electrons along the magnetic field dramatically alters the structure of the dissipation region around the X-point. Thermal streaming introduces a new physical scale length ρ_s into the resistive MHD equations, where ρ_s is the ion gyroradius based on the electron temperature. The dissipation region develops a two scale structure: a very small inner current layer and a somewhat larger flow layer in which the plasma flow is guided. Along the inflow direction to the X-point, the width of the extremely narrow current layer is proportional to the plasma resistivity η , while the outflowing plasma is guided in a broader channel of width ρ_s . In the outflow direction, the length of the current layer is given by ρ_s , while the length L of the flow layer is macroscopic. As the reversed magnetic field lines are convected towards each other at the X-point, they are compressed in a layer of width ρ_s about the X-point. After reconnection, the tension in the compressed magnetic field lines is released accelerating the outflowing plasma to high speed. As a consequence, our simulations demonstrate that the inflow speed to the X-point is virtually independent of both η and ρ_s . Thus, the surprising conclusion from our simulations is not only that the reconnection rate is enhanced in high temperature plasmas by electron thermal streaming, but also that the rate of reconnection remains large as both η and ρ_s become small.

3. Dynamics of Sawtooth Collapse in Tokamak Plasmas

The nature of sawtooth collapse in tokamak plasmas has been a major puzzle since the observations on the TEXTOR³⁵ tokamak (and later on many other tokamaks) indicating that the central safety factor q_0 remains well below unity after the collapse. This is not consistent with the standard Kadomtsev reconnection model in which q_0 is close to unity after the reconnection. In the present work³⁶ the nondissipative effects in the Ohm's Law are included. Under conditions where dissipative processes are weak, the reconnection is dominated by the nondissipative effects. As a consequence after the reconnection the magnetic energy is transformed into flow energy. In the traditional Kadomtsev reconnection the magnetic energy is mostly dissipated so that the energy that goes into the generation of flow is very small. It is the generation of

this flow in the nondissipative case, which leads to a partial inversion of the helical flux distribution and a final q value distinctly below one. Thus during one cycle of the sawtooth the initial state with $q_0 \sim 0.75$ undergoes a fast “nondissipative” reconnection which raises the q on axis to unity momentarily. The strong flow generated by the fast reconnection then redistributes the helical flux and reduces the q on axis to values below unity. This scenario has been substantiated by detailed 2D MHD simulations. The present theory also explains the observation of the snake phenomenon, where a density blob at the $q = 1$ surface appears “unaffected” by the reconnection process.

4a. Influence of Trapped Thermal Particles on the $n = 1$ Kink in High Temperature Tokamak Plasma

Energetic trapped particles are known to strongly modify the stability properties of the $n = 1$ internal kink mode in tokamaks. In high temperature discharges, similar interactions involving thermal particles can be shown to be important.³⁷ When considering such interactions, it is essential to include the coupling to electrostatic perturbations that give rise to perturbed parallel electric fields. Thus, one is led to investigate the interaction between magnetic, MHD-like modes and electrostatic trapped particle modes. In order to study this interaction, we have modified the global stability code MARS to include the effects of trapped particles, both ions and electrons, and electrostatic perturbations. Using the code, we have investigated the stability of various profiles for circular and JET-shaped cross sections. The stability of the pressure-driven, ideal $n = 1$ mode is strongly modified by the trapped particles. When the electrostatic potential is neglected, the trapped particles are generally stabilizing. However, with only one trapped species (electrons or ions), cases unstable in ideal MHD remain unstable and the mode acquires a significant rotation frequency. With both species of trapped particles treated by drift kinetic theory, the rotation is much reduced and the mode is stabilized well above the ideal-MHD threshold. If the electrostatic potential is retained, the mode structure can be strongly modified by the trapped particles via coupling of the $m > 1$ side-bands to trapped particle modes, and the stabilizing effect is lost. Our results indicate that in high temperature tokamaks the linear stability on $n = 1$ modes is dominated by trapped particle effects.

4b. Effect of Trapped Particles on MHD Modes

The dynamics of the central region of high temperature tokamak plasmas is frequency dominated by the so-called sawtooth oscillations giving rise to a more or less periodic redistribution of the energy and magnetic flux in the region. The trigger of these relaxations is the internal $n = 1$ kink mode, where n is the mode number for variation of quantities in the toroidal direction. This mode corresponds to a nearly rigid shift of the internal region of the plasma. Its suppression or control is considered to be important in present and future tokamaks. In its ideal and most robust form, to which we restrict attention here, it grows on the timescale over which the plasma is ideally conducting.

Energetic trapped particles are known to strongly modify the stability properties of the $n = 1$ internal kink mode in tokamaks. Recently we have shown that similar interactions involving thermal particles are important³⁷. When considering such interactions, it is essential to include the coupling to electrostatic perturbations that give rise to perturbed parallel electric fields. Thus, one is led to investigate the interaction between magnetic, MHD-like modes and electrostatic trapped particle modes. In order to study this interaction, we have modified the global stability code MARS to include the effects of trapped particles, both ions and electrons, and electrostatic perturbations. Using the code, we have investigated the stability of various profiles for circular and JET-shaped cross sections. The stability of the pressure-driven, ideal $n = 1$ mode was found to be strongly modified by the trapped particles.

Our efforts during the past year have focussed on modifying the code so as to allow for magnetic reconnection. This is because the threshold for the resistive $n = 1$ reconnecting mode can be quite different from that of the ideal mode. Modification of the code to treat reconnecting modes requires significant changes since the perturbed quantities are no longer conveniently expressed in terms of the magnetic field line displacement which becomes singular on a rational surface. A variational formulation of the problem has been developed which can be implemented numerically. This variational formulation allows one to treat the physics of the reconnecting layer using a variety of models. Implementation of the model is being carried out in collaboration with Anders Bondeson now at Uppsala University in Sweden.

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