MARYLAND CONTROLLED FUSION RESEARCH PROGRAM

Progress Report

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PROGRESS REPORT

The theoretical research activity at the University of Maryland supported by the Department of Energy focusses on two major tasks. They are

- (A) Transport, Generation of shear flow and L-H transitions in Tokamaks
- and
- (B) MHD Stability of Tokamaks

In the following pages we will summarise the progress made by the group over the last year.

TASK A

(1) Poloidal Rotation of Tokamak Plasmas at Super-Poloidal-Sonic Speeds¹ (Hassam)

In this work, the equilibrium and stability of tokamak plasmas, rotating at speeds in excess of the poloidal sound speed have been studied. This work is motivated by the propositions that (1) shear in the poloidal flow suppresses turbulence, and (2) that for poloidal flows beyond the poloidal sound speed the suppression would be substantial. It is shown that for super-poloidal-sonic flows, but sub-poloidal Alfvénic flows, the only modification of the MHD equilibrium is a small enhanced Shafranov shift. Also it is shown that the damping rate for the poloidal flow falls off as the square of the poloidal speed. Thus the power requirement for an external drive maintaining this flow becomes more favorable to this regime even for reactor-relevant plasmas. Another important aspect of these equilibria is that such large flows reduce the fraction of trapped ions significantly. Thus neoclassical, as well as anomalous transport driven by trapped particles would be reduced.

This work was done, in part, while Dr. Hassam was on sabbatical at General Atomic. While at GA Dr. Hassam submitted a proposal to induce core poloidal rotation in DIII-D using neutral beams. This proposal was accepted and the experiment is currently scheduled for September 1994. In the meantime Dr. Hassam has maintained close contact with GA experimentalists to provide the necessary theoretical support in planning this experiment.

(2) Rotation of Plasmas in Neoclassical Regimes (Antonsen, Galeev, Hassam, Liu, Novakovski and Sagdeev)

The rotation of plasmas in different neoclassical collisionality regimes has been studied. Earlier numerical work by Hsu et. al.² has shown that the plasma inertia increases in the banana regime, which leads to changes in the rotation dynamics of the plasma. We have developed an analytical model with time-dependent drift-kinetic equations. Using the ratio of the bounce period to the evolution time for the rotation as a smallness parameter, we have obtained general results for the magnetic pumping rate, the neoclassical Stringer spin-up rate and the effective plasma inertia. The

Stringer spin-up³, which was initially studied in the Pfirsch-Schluter regime survives in the banana/plateau regime. We have simplified the collisional term in such a way that the inertia becomes a function of only two parameters, q , the safety factor and ν_* , the effective collision frequency. We have shown that the enhancement in inertia in the plateau regime is slightly smaller than the usual $(1+2q^2)$ term in the Pfirsch-Schluter regime. However in the banana regime the enhancement is given by $1+q^2/\epsilon^{1/2}$, where $\epsilon=a/R$ is the inverse aspect ratio⁴. The simplicity of the model allows for extension of the model to nonlinear studies. This work was also partially supported by the US/CIS DOE contract

(3) New Unstable Branch of Drift Resistive Ballooning Modes in Tokamaks.⁵ (Novakovski, Guzdar, Drake and Liu)

During the last two years we (McCarthy et al.⁶ and Guzdar et al.⁷) have advocated Drift Resistive Ballooning modes as the cause of anomalous transport in the edge region of tokamaks based on numerical studies both linear and nonlinear. In the present work we have re-examined the linear stability of such modes. We find analytically that for small magnetic shear $s=rq/q \ll 1$, there are basically two unstable branches of the resistive ballooning modes. One branch is the conventional branch which has been studied by numerous authors using the two-space scale analysis. This conventional branch is more unstable than the second branch found by us in the weak shear limit. However for $s \sim 0(1)$ the conventional branch is found to become stable, while the new branch, which is more strongly ballooning, is robustly unstable. This work "explains" the strongly ballooning modes observed in our 3D simulations⁷ and further reinforces our contention that these modes are a prime candidate for causing edge transport in tokamaks. This work was also partially supported by the US/CIS DOE contract.

(4) 3D Fluid Simulations of the Drift Resistive Ballooning Modes-Twisted Coordinate System⁸ (Guzdar, Drake and Hassam)

We have modified our three-dimensional fluid code for the Drift Resistive Ballooning Modes. The reduced Braginskii Equations are now solved in a fully twisted coordinate system⁹. Also in the radial direction we have now introduced periodic boundary conditions. The transformation to the twisted coordinate system allows us to use significantly larger time steps for realistic values of the magnetic shear $rq'/q=1\sim 2$. The periodic boundary condition prevents the quasilinear flattening of the density since the outgoing flux at the right boundary equals the incoming flux at the left boundary. In the direction along the fieldline we have introduced Neumann boundary conditions for the density and the potential, and Dirichlet condition for $v_{||}$. With these two modifications we have found that in the absence of quasilinear flattening, the particle flux is significantly larger than that obtained in our earlier simulations. The magnitude is now consistent with experimental values. We also observe a strong localisation of the turbulence along the field line, consistent with the strong ballooning character reported in our earlier simulations. The level of the density fluctuations are typically between 20-30%. These results further support our point of view that the Drift Resistive Ballooning Modes are a very promising candidate for explaining edge fluctuations and transport in tokamaks.

(5) Disintegration of Ion Banana Orbits in Tokamak Edge Plasmas¹⁰ (Lau, Drake, Guzdar and Hassam)

Ion orbit loss is a mechanism believed to be responsible for the radial electric field observed in the edge region of tokamaks¹¹. 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 fluctuations. 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.

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TASK B

(1) Fast Reconnection in High Temperature Plasmas¹ (Kleva, Drake)

Simulations of magnetic field line reconnection in high temperature plasmas, which include the effect of pressure forces acting on the electrons, have been completed. The electron pressure introduces a new physical scalelength ρ_s , the ion gyroradius based on the electron temperature, into the resistive MHD equations. The single dissipation layer of resistive MHD is split into two distinct layers by this effect: a small inner current layer and a larger flow layer. Unlike resistive MHD, the current is microscopic in the outflow, as well as the inflow, direction. As a consequence, the current layer is not unstable to the formation of secondary magnetic islands at low values of resistivity, and the patchy reconnection which occurs in resistive MHD at low resistivity does not occur when the physics of the electron pressure force is included in the analysis. The absence of a strong current sheet in the outflow region enables the magnetic nozzle controlling the outflow to open up. As a consequence the magnetic reconnection rate remains large as the resistivity and ρ_s become small.

(2) Dynamics of sawtooth collapse in tokamak plasmas² (Biskamp, Drake)

The nature of sawtooth collapse in tokamak plasmas has been a major puzzle since the observations on the TEXTOR³ 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 work the nondissipative effects in the Ohms 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.

(3) Effect of Trapped Particles on MHD modes^{4,5} (Antonsen and Bondeson)

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 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 important^{4,5}. 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.

(4) MHD Stability of High Beta Toroidal Equilibria⁶ (Kleva, Drake)

A 3D numerical code has been developed which solves the compressible nonlinear MHD equations in toroidal coordinates. Because the code solves the MHD equations on a spatial grid, the code is well suited for the simulation of the steep gradients for the pressure and magnetic field gradients at high beta. Such gradients cause spurious ringing in spectral codes unless a very large number of Fourier modes are retained in the code. We have used our code to obtain tokamak equilibria at high beta $\epsilon\beta_p > 1$, where β_p is the poloidal beta and ϵ is the inverse aspect ratio. These equilibria are characterised by an outer boundary layer surrounding an inner core in which the poloidal flux is solely a function of the major radius R , in agreement with the analytic

prediction of Cowley et al.⁷. We have tested the stability of these high beta equilibria to low n MHD kink modes, where n is the toroidal mode number. We find that the low n MHD kink modes are highly unstable in high-beta equilibria, and that the growth increases as β_p increases.

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