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THE TILT MODE TURBULENCE AND TRANSPORT IN FIELD-REVERSED CONFIGURATIONS

A field-reversed configuration (FRC) is a compact toroidal (CT) plasma confinement geometry with negligible toroidal magnetic field (Fig. 1). Plasma confinement is provided by a poloidal magnetic field associated with diamagnetic toroidal current carried by the plasma toroid. Such a configuration has intrinsically high β (the magnetic field vanishes on a circle in the plasma core), and may be translated and compressed. These features make the FRC attractive as a confinement geometry for magnetic fusion. Elongated (prolate) FRCs have been produced in a number of experiments and have demonstrated macroscopic stability. When the rotational $n = 2$ mode is controlled by external multipole fields, plasma confinement for the order of 100 axial Alfvén transit times is observed. Information about field-reversed configurations can be found in two review articles [1,2].

An outstanding theoretical problem of great importance in research on FRCs is the explanation of the observed stability of FRCs to the internal tilt mode. For example, in the Los Alamos FRX-C experiment, FRCs showed no evidence of the internal tilt mode during experimental lifetimes of up to 300 μs, which is over an order of magnitude longer than the expected ideal MHD growth time. Finite-Larmor-radius (FLR) theory is inappropriate for the FRC configuration and the observed stability has not been explained by FLR theory [3]. We are engaged in MHD and kinetic studies of the tilt mode that are aimed at explaining the observed stability in FRC experiments. These studies are within the contexts of two physical models: resistive MHD and the Vlasov-fluid model (collisionless ions, massless fluid electrons) [4]. Computer codes that implement both linearized and fully nonlinear versions of these models are being used. Our results do not yet provide an adequate explanation of the observed stability, although a strongly stabilizing tendency due to kinetic ion effects has been observed. The effects of plasma rotation appear to be unimportant. It seems most likely that a combination of profile effects, ion kinetic effects and nonlinear effects will be required to understand the gross stability of FRCs.

The theoretical and simulational evidence for interior turbulence in FRCs is overwhelming [5,6]. For investigating the important subject of turbulence and transport in FRC's, we use both analytic studies and numerical simulation. A conclusion of our investigations is that FRC transport laws should not be based on lower-hybrid-drift (LHD) modes localized near the separatrix, but should be based on low-frequency turbulence occurring throughout the FRC profile. Previous simulations of the racetrack region of an FRC on a short time scale have shown that LHD turbulence develops quickly in the edge region [6]. In our new long-time simulations, low-frequency modes are present that interact with the LHD modes. Turbulence eventually develops throughout the interior of the FRC and causes destruction of magnetic flux. Work is in progress to determine transport coefficients in the end regions and the magnitude and scaling of the flux and particle losses that are implied by the simulations.

1. THE TILT MODE

To follow the nonlinear evolution of the tilt mode, including Hall effects and effects of rotation in the equilibrium, we are using the resistive MHD model [7]. An analytic treatment [8] has predicted that the inclusion of the Hall term can lead to stability for small values of the parameter s, which is an average number of ion gyro-radii across the plasma, or for very large elongations. Except near the predicted transition between stability and instability, numerical results with the resistive MHD model are in qualitative agreement with the analytic results. However, just before the predicted transition to stability, the character of the $n = 1$ mode suddenly changes and a new mode, with much more radial structure and a growth rate of about 50% of the MHD growth rate, becomes dominant. Inclusion of rotation in the resistive model at the experimentally observed rates has almost no effect unless the rotation speed at the separatrix is nearly sonic, in which case the character of the tilt changes. The displacement becomes axial and there is gross distortion of the separatrix, but the growth rate remains comparable to that of a nonrotating FRC. Various equilibria have been examined with the resistive MHD model, including two new classes: FRC's with strong axial mirrors and FRCs with flux maxima near the ends. No significant differences in growth rate have been observed among the equilibria that were examined.

We are using two techniques to study the internal tilt mode within the context of the linearized Vlasov-fluid model [4]. In this model the ions are described by the Vlasov equation and the electrons are treated as a massless, pressureless fluid. The first technique is based on a dispersion functional that is particularly appropriate for use with multidimensional equilibria [9, 10]. The dispersion functional is expressed in terms of autocorrelation functions of certain quantities taken along the equilibrium particle orbits. The dependent variable for the Vlasov-fluid model is the magnetic field line displacement ξ . By expanding ξ in terms of a finite set of basis functions, a dispersion matrix can be derived from the dispersion functional. The eigenfrequencies of the problem are the roots of the determinant of the dispersion matrix and the eigenmodes are the eigenfunctions of the dispersion matrix corresponding to zero eigenvalue. Displacements are presently restricted to be constant on an equilibrium flux surface and to have no radial component. Plans to remove this approximation are now being formulated.

Our study with the dispersion functional approach has brought to light a change in the ordering of the growth rates of the modes as s is decreased. The kinetic mode with the least structure grows more slowly than its MHD counterpart. However, for s approximately 2 or smaller this mode is no longer the fastest growing mode. Calculations are being done to determine how kinetic stabilization changes with plasma elongation. We observe a decrease in kinetic stabilization with increasing elongation.

Work is in progress to determine the stability of large-s FRCs to which has been added a hot ion component in addition to the thermal component.

Our second technique for using the linearized Vlasov-fluid model to examine the internal tilt mode is to solve the equations as an initial-value problem. The perturbation distribution function is computed from the linearized Vlasov equation by integration along unperturbed orbits, thereby avoiding the limitation of a linearized particle simulation that arises from exponential separation of neighboring particle orbits [11]. Results obtained are in general agreement with the dispersion functional approach.

We have modeled the nonlinear evolution of the internal tilt mode within the context of the Vlasov-fluid model with a 3-D particle-in-cell code (QN3D) [12]. This nonlinear code models the plasma by using particles for the ions and a massless zero-temperature fluid for the electrons. These assumptions, along with neglect of the displacement current in Ampere's law, eliminate high-frequency modes of the plasma and allow one to study ion kinetic effects on MHD modes. QN3D uses 2-D axisymmetric output from another code [13] to initialize the positions and velocities of the particles as well as the magnetic field. QN3D is a very large code, typically using a million particles and a grid size of 41 × 41 × 41. Two extensive calculations are reported, each involving 3000 time iterations. The two calculations correspond to s values of 1.6 and 12. The estimated linear growth rates for these two cases are in fair agreement with linear Vlasov calculations. Exact agreement should not be expected since the initial equilibria used by the nonlinear and linear calculations are somewhat different. In order to compare the results of QN3D with MHD predictions, we use a 3-D MHD code, TEMCO [14], to compute growth rates in the MHD limit. This code, when run with the same equilibrium as QN3D, gives comparable growth rates in the high-s case. Computations are now under way to simulate the further nonlinear evolution of the tilt mode.

2. TURBULENCE AND TRANSPORT

The interior of an FRC is unstable to a set of low-frequency, high-β, electromagnetic drift waves [15]. The electromagnetic nature of the modes causes rapid radial heat exchange between the interior and the exterior, as well as particle transport. The magnetic fluctuations produce an anomalous resistivity in the interior, which reduces the internal magnetic flux. A weak turbulence analysis based on these unstable modes has been used to derive particle, flux and energy loss rates, which agree with experiment over a wide range of parameters. An analysis of three-wave interaction between the low-frequency modes and LHD waves indicates that the low-frequency turbulence can reduce the level of lower-hybrid-drift wave turbulence; this agrees with both the null measurements of LHD turbulence in TRX-2 [16] and the opposite result in the Garching theta pinch INTEREX [17]. These results confirm that low-frequency modes are necessary ingredients for describing FRC transport.

Our particle simulations [18] examine the microstability properties of an FRC with infinite axial extent and planar geometry. In this geometry, the racetrack region is approximated by a planar slab and the end regions are absent. The plasma evolution is described by a finite-electron-mass hybrid code in which the ions are kinetic and the electrons are a finite-mass charge-neutralizing fluid. Waves characteristic of the lower-hybrid-drift instability quickly grow in the region near the separatrix where the driving density gradient is large. Nonlinear waves ultimately fill the entire region. As the simulation is run for longer times, lower-frequency waves enter the simulational domain and interact with the higher-frequency waves. There is some evidence that the saturation amplitude of the higher-frequency waves near the separatrix decreases in time. Although no classical Coulomb collisions are included in the model, magnetic flux is nevertheless destroyed at later times. The time that elapses before flux destruction commences scales approximately with v_i/r_s, where v_i is the ion thermal speed and r_s is the separatrix radius.

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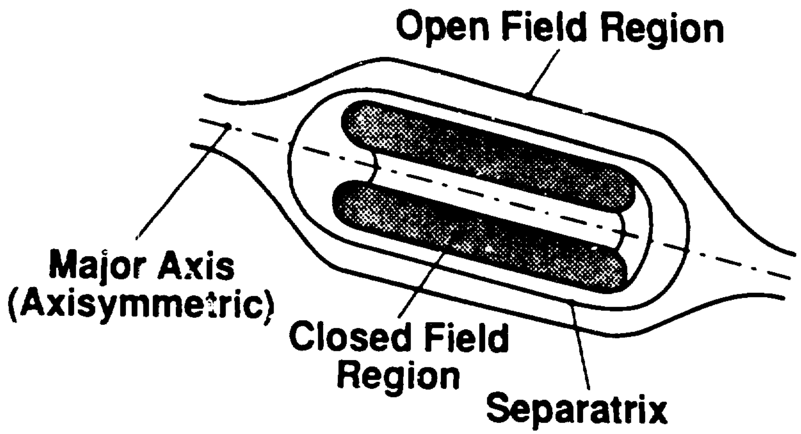
FIGURE CAPTIONS

Fig. 1. FRC Geometry.


Open Field Region
Major Axis
(Axisymmetric)
Closed Field
Region
Separatrix