STABILIZATION OF THE TEARING MODE
BY TURBULENT DIFFUSION AND RUNAWAY ELECTRONS

by

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Submitted to the Department of Nuclear Engineering
on January 29, 1986 in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

ABSTRACT

A fully kinetic analysis of the $m = 2$ tearing mode is performed for a tokamak plasma including the effects of turbulent electron diffusion and runaway electrons. Turbulent diffusion is included in the analysis by applying the normal stochastic approximation (NSA) to the collisionless drift kinetic equation (DKE) for electrons. A kinetic analysis inherently allows for the choice of various equilibrium electron velocity distributions, thus enabling a comparison between a drifted Maxwellian and a runaway-type distribution. This analysis is fully electromagnetic, including the effects a magnetic fluctuation potential $\hat{A}_1$ as well as a finite electrostatic potential $\phi$, and is valid in the low-beta, low-frequency regime. The electron response is obtained by applying the NSA to the DKE, and the ion response is given by the linearized Vlasov equation. Ampere's law and quasineutrality are then used to derive a set of coupled, self-adjoint equations for the fluctuation potentials $\phi$ and $A_1$. Solutions to this set of equations describe both unstable finite-$\beta$ drift waves when analyzed for high $m$ modes and the tearing mode when analyzed for low $m$ modes (where $m$ is the poloidal mode number).

In the NSA, the tearing mode is assumed to exist on a background of drift wave turbulence. The underlying drift waves produce overlapping phase space islands, which lead to stochastic electron orbits. The NSA exploits the properties of stochastic orbits to replace the nonlinear fluctuation terms in the orbit operator of the DKE with a radial diffusion operator, $-D_e \partial^2 / \partial x^2$, where $D_e$ is the electron diffusion coefficient. Results for the tearing mode indicate that stability is obtained for sufficiently large values of the diffusion coefficient. Provided $D_e \sim 1/n$, this implies that a density threshold must be surpassed before the tearing mode is observed. Physically, turbulent electron diffusion prohibits the formation of a perturbed parallel current within a finite diffusive correlation distance $x_c \sim D_e^{1/3}$ of the rational
surface. This cuts into the available energy driving the tearing mode and reduces it from $\Delta'(0)$ to a value of $\Delta'(x_c)$. Here, $\Delta'(x_c)$ is the difference between the logarithmic derivative of $A_\parallel$ evaluated at a distance $x_c$ from the rational surface and that value at a distance of $-x_c$. Since $\Delta'(x)$ is typically a decreasing function of $x$, then stabilization occurs when $x_c > W$, where $W$ is the nonlinear island saturation width given by $\Delta'(W) = 0$.

When a runaway-type distribution is used for the equilibrium electron distribution in the place of a drifted Maxwellian, the real frequency of the tearing mode is shifted to a value above the electron diamagnetic frequency $\omega_{ce}$ by an amount $\delta \omega \sim n_b v_b$. Here, $n_b$ is the density and $v_b$ the velocity of the fast electron beam which is used to model the runaway-type current. In addition, a new stabilizing term appears in the expression for the growth rate proportional to $\delta \omega$. Physically, this stabilizing term represents the additional energy necessary to maintain the particle motion at the frequency $\omega_{ce} + \delta \omega$. Since $\delta \omega = 0$ for a drifted Maxwellian equilibrium, this implies that stability is greater when a fast electron population is present. At higher densities, these fast electrons relax back into the bulk population due to the increased collisionality. Hence, the tearing mode stability is enhanced at low densities due to the presence of runaway electrons. This runaway stabilization is a higher order effect, however, and is only important for a tearing mode near marginal stability.

The inclusion of a finite electrostatic potential gives an additional stabilizing term to the dispersion relation, which physically represents ion inertial effects. This ion inertial effect implies that, in the absence of both turbulent diffusion and runaway electrons, the tearing mode is stabilized for ion betas $\beta_i$ above some critical value, $\beta_{i*}$, where $\beta_i \sim \Delta'(0)$. Hence, this ion inertial stabilization at high density, combined with the stabilization by turbulent diffusion and runaway electrons at low density, implies that it may be possible to operate a tokamak in a plasma regime which is stable to the $m = 2$ tearing mode at all densities. For typical Alcator C parameters, a tearing mode island of width $W \sim 0.1$ cm is suppressed for $D_e > 10^4$ cm$^2$/sec and highly MHD unstable profiles providing large $\Delta'(0)$ are stabilized for $\beta_i > 10^{-3}$.

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