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I. Toroidal Alfvén Eigenmode Induced Ripple Trapping

R. B. White, E. Fredrickson, D. Darrow, M. Zarnstorff,
R. Wilson, S. Zweben, K. Hill, Yang Chen, Guoyong Fu

Collective alpha-driven instabilities such as the toroidicity-induced Alfvén eigenmodes (TAE) are of concern for future tokamak devices since they can induce anomalous alpha losses. Previously discussed mechanisms of particle loss have consisted of induced transition from passing to direct-loss trapped orbits and radial diffusion produced by stochasticity in particle orbits caused by overlapping resonances.¹⁻³ In this work we point out a very effective loss process in devices possessing magnetic ripple wells. The effect has been observed in the Tokamak Fusion Test Reactor⁴ (TFTR), where particle fluxes intense enough to damage the vacuum wall were observed. Consider a trapped particle whose banana tip is in the vicinity of a ripple well below the midplane, i.e. the particle passes over a local well before bouncing. Ripple trapping occurs due to the fact that a particle is radially further outward after bouncing than before, due to the banana width. Field ripple increases strongly in this direction and thus the particle encounters larger ripple after bouncing, and may be trapped in the well. If this occurs it drifts vertically to the wall and is lost. Since the well location varies due to the toroidal precession, eventually all trapped particles on orbits with bounce points intercepting the ripple well domain will be lost. The presence of a time dependent magnetic perturbation such as the TAE mode produces additional modulation of the particle position which can greatly increase the phase space of particles capable of making the transition to a trapped state. If the initial particle distribution extends to the domain of ripple trapping, there is no threshold amplitude for this process, and since particle orbit excursions are linear in the perturbed field amplitude, the loss is also approximately linear.

To demonstrate the mechanism we model the high energy particle distribution, equilibrium, and mode structure approximating those present in TFTR during the observation of this effect. The high energy particle distribution produced by heating was observed to cause destabilization of the TAE mode, in agreement with numerical analysis used to determine the growth rate and eigenmode profiles. The code and the analysis used has been pre-

viously described.^{5,6} The toroidal mode number observed was $n = 4$ and we include all important poloidal harmonics, i.e. $m = 4 - 12$. The mode frequency used was the experimentally observed TAE frequency of 188 kHz. However we find that the results are relatively insensitive to the form of the eigenmode used, as long as the mode amplitude is significant near the ripple trapped domain.

Simulation is done using a Hamiltonian guiding center code ORBIT described previously.^{7,8}

The equilibrium had a major radius $R = 262\text{cm}$, $B = 3$ Tesla on axis, a minor radius $a = 100\text{cm}$, with a safety factor of $q = .8 + 3.2(r/a)^2$. The particle distribution is a model high energy Hydrogen minority tail ion distribution chosen to fit that produced during the experiment, with $T = 370$ keV, and 75% trapped particles.

Figure I.1: TAE induced ripple trapping on TFTR

Two populations of lost particles were observed in the simulations, those with banana orbits intersecting the wall, having pitch $\lambda = v_{||}/v \approx .5$ and impacting the wall just below the midplane, and the ripple trapped population, with $\lambda \approx 0$, intersecting the wall at a location determined by the existence of ripple wells and by the TAE amplitude. An example of a TAE induced ripple trapping event is shown in Fig. 1. The ripple trapped population peaks near $R = 315\text{cm}$ which corresponds to the smallest value of R at which the ripple trapped domain extends across the plasma vertically including the high density central domain. The simulations consisted of observations of the total losses produced by a one millisecond TAE burst at a fixed amplitude and frequency. Because of the broad distribution and large banana width of the orbits, loss to the outer midplane begins at amplitudes well below stochastic threshold. There is no threshold amplitude for the ripple trap loss process, the total flux being approximately linear in the mode amplitude. At zero amplitude there is a small flux due to that part of the distribution extending to the ripple well domain.

Three different observations confirm the model sketched above. First, intense metallic influxes are observed in the plasma, predominantly of manganese. Second, thin stainless steel debris shields located at the bottom of the vacuum vessel at a major radius of 305 cm were melted. Third, strong fluctuations were measured in the expected TAE frequency range during the experiments.

In conclusion, high energy particle loss consisting of ripple trapping induced by high frequency MHD perturbations has been modeled and observed in TFTR. The mode observed was a TAE mode destabilized by the high energy tail produced by ICRF heating, but any high frequency mode could produce similar results. Finally we point out that this loss mechanism is not effective for the alpha particle distribution in the International Thermonuclear Experimental Reactor⁹ ITER because of the very small ripple well domain. However modification of coil design or major radius would require a reexamination of this process.

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II. High- β Disruption in TFTR

W. Park, E.D. Fredrickson, A. Janos, J. Manickam, W.M. Tang

In the record-setting deuterium-tritium discharges in TFTR, performance is limited by MHD activity, the most dangerous type being the major disruption. This event causes the loss of the confined thermal energy during the thermal quench phase and then the loss of plasma current during the current quench phase.^{1,2} For larger tokamaks like ITER, a major disruption can cause substantial damage to the first wall.

We use the nonlinear 3D MHD code, MH3D,³ to study high- β disruptions; i.e., major disruptions near the β limit. First we obtain a 2D toroidally symmetric equilibrium state using the safety factor q and pressure profiles which correspond to a representative experimental case. The case presented here has $q_0 = 0.92$ at the axis, $q_w = 4$ at the boundary, and $\epsilon\beta_p = 0.3$ with the aspect ratio $R/a = 2.9$. From this 2D equilibrium, a linear $n = 1$ mode with a dominant $m = 1$ component is obtained. This ideal mode nonlinearly evolves to a helically distorted 3D equilibrium as shown in Fig. 1(a). This figure shows the equi-pressure contours in the poloidal plane at three different toroidal angles. The maximum pressure gradient occurs at the toroidal angle $\phi = 0$ plane where the local steepening of the pressure gradient occurs in the bad curvature region (the outboard region).⁴

The MH3D code is modified to be able to calculate a mixed- n linear eigenmode evolving from such a 3D equilibrium. A rapidly growing linear ideal mode is obtained. The mode is localized at the peak pressure gradient at the outboard region. A similar mechanism for this type of linear mode development has been suggested in analytic studies,^{5,6} and some of the associated features have been experimentally observed.⁷ The crucial question which will be investigated in the following deals with the nonlinear development of this toroidally localized high- n mode; i.e., whether it will cause a disruption, or just cause a local enhancement of dissipation due to its radial localization, or even saturate harmlessly as in the low- n case.

The nonlinear calculation shows that the steep localized pressure gradient, which gives rise to this toroidally localized high- n mode, becomes even more steep nonlinearly. This causes the nonlinear mode to be increasingly localized producing a local pressure bulge which strongly pushes into the outer region

Figure II.1: (a) Pressure contours of the 3D equilibrium. (b) The later non-linear time development of the pressure.

of plasma as shown in Fig. 1(b), which plots the temporal evolution of the pressure contours at $\phi = 0$. (For the nonlinear study, a slightly different q profile is used as explained in the full paper.) The local pressure bulge continues to push into the outer region of plasma until it causes most of the plasma region to become stochastic and thereby produce a thermal quench.

The novel nonlinear behavior just described can be understood from an examination of the linear eigenmode. The fastest growing eigenmode arising from the 3D equilibrium can have either a positive or a negative sign. Since the positive sign gives an outboard direction of flow at the position of the local steep pressure gradient, it will further steepen this gradient and make

it more localized. This accordingly provides a stronger drive to the mode.

Figure II.2: ECE signals; (a)theoretical and (b)experimental.

Figure 2(a) shows the simulated ECE signal obtained. The signal is produced by two toroidal rotations with 15 detector sites with the lowest line corresponding to $r = -0.9$ at the inboard region and the uppermost line to $r = 0.9$ at the outboard region. The high- n oscillations are only seen when the underlying $n = 1$ signal is at the maximum phase because this mode is strongly localized toroidally. The calculated signals are in good agreement with the experimental ECE data shown in Fig. 2(b). Specifically, note that the experimental signal shows similar high- n oscillations superposed on the maximum phase of the $n = 1$ signal. This confirms that the "bursts" of the high- n mode are actually due to a steadily growing localized high- n mode driven by a nonlinear $n = 1$ distortion. It is only seen when the toroidally localized mode structure comes into view of the ECE detector thereby giving the bursting behavior.

After the thermal quench, a 95% reduction of pressure in the simulation causes the flux surfaces to recover. However, they contain large magnetic

islands in the outer region. (The total pressure loss is usually less than 95%, but the behavior is similar.) This indicates that there exists some pressure confinement in the central region in the post thermal quench phase. This also agrees with the experimental observation of some pressure recovery in the central region. Such behavior can be understood by the fact that at small β , the plasma is stable to ideal modes while unstable to resistive modes if the perturbation is large enough. The large perturbation resulting from the thermal quench phase destabilizes the resistive ballooning mode, overcoming the layer stabilization effect of Glasser, Green, Johnson.⁸

The likely final phase of a major disruption occurs when Z_{eff} becomes high, and the plasma becomes very cold due to line radiation. Since the loop voltage in the experiment is not large enough to sustain the plasma current, the current quench phase sets in to terminate the discharge.

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III. Theory Publication for January 1995 – March 1995

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IV. Theory Visitors for January 1995 – March 1995

Artun, M., Dept. of Physics, UCLA, January 30 – February 5, 1995.

Boozer, A., Columbia University, February 16-17, 1995.

Decyk, V., UCLA, January 26, 1995.

Hsu, C. T., MIT, January 1 – December 3, 1995.

Ichiguchi, K., National Institute for Fusion Science, Japan, March 9 – April 1, 1995.

Rogers, B., Institute for Plasma Research, Maryland University, February 2-5, 1995.

Zabiego, M., University of Wisconsin, January 12, 1995.

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