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BY

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Causes of Major Tokamak Disruptions

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ABSTRACT

The nonlinear saturation theory of the tearing mode is used to examine the necessary conditions for the occurrence of a major tokamak disruption. The results are compared with full three-dimensional numerical simulations, and with experimental data.

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Major disruptions present perhaps the most serious design problems for reactor size tokamaks. They occur particularly under conditions of high plasma current and density.¹⁻⁸ Because of the large plasma energy (~300 MJoules) a disruption in a device of the size of the Engineering Test Facility (ETF) or the International Tokamak Reactor (INTOR) could produce vaporization of kilograms of wall material if the deposition were spatially localized, in addition to serious thermal wall stresses and coil stresses. In this letter, we explore the necessary conditions for the occurrence of a major disruption.

There now exists a fairly large body of experimental data which indicates that the major disruption is associated with the development of a large $m/n = 2/1$ magnetic island.¹⁻⁸ Here m, n refer to poloidal and toroidal mode numbers, i.e., the perturbation from axial symmetry is of the form $\exp[i(m\theta + n\phi)]$. The growing $m = 2$ mode gives rise to the magnetic oscillations and precursors seen on x-ray emissivities due to island rotation. Disruptions also occasionally occur without a precursor oscillation, but the absence of this signal is believed to be due to the island being stationary, perhaps because of interaction with the limiter.⁶

There is good experimental and computational evidence that the disruption itself, a rapid drop in plasma temperature and a slower loss of current, may be caused by either the $2/1$ mode becoming large enough⁹ to destroy magnetic surfaces by overlap with a $3/2$ island,¹⁰ or by contact of the $2/1$ island with the limiter.¹¹ There are other mechanisms proposed to be important in

the final stages of the disruption,^{12,13,14} but these are less well documented experimentally and are not considered here. Limiting ourselves to these two possible causes of a disruption, we are able to use a very simple code to map out the values of operating parameters for which disruptions are likely to occur, and to distinguish the most probable cause for each event.

Growth of magnetic islands in an axisymmetric equilibrium is due to the relatively lower magnetic energy of the island state. The growth of the island requires magnetic reconnection and, thus, the growth rate is a hybrid between the ideal magnetohydrodynamic time scale and the resistive time, but the driving forces are basically magnetic. Nonlinear saturation occurs when the island reaches a state which is a magnetic energy minimum. In cylindrical geometry, the magnetic energy of a small island state is proportional to the quantity Δ' , determined through linear theory by the current profile,^{15,16} and nonlinear saturation¹⁷ is given approximately by the vanishing of a generalization of this quantity to an island state of width w , $\Delta'(w)$. This description remains valid when finite Larmor radius effects are taken into account.¹⁸

The vanishing of $\Delta'(w)$ determines the magnetic energy minimum, and can be used to examine, as a function of current profile parameters, conditions leading to a major disruption, namely, the possibility of a large 2/1 island near the limiter or the overlap of a 2/1 island with a 3/2 island. We parameterize the safety factor profile $q(r) = rB_\phi / RB_\theta$ through

$$q(r) = q(0) [1 + (r/r_0)^{2\lambda}]^{1/\lambda} \quad (1)$$

with the associated current profile

$$J(r) = \frac{2B_0}{Rq(0)} \frac{1}{[1 + (r/r_0)^{2\lambda}]^{1+1/\lambda}} \quad (2)$$

Here r is the minor radius, normalized to the plasma edge (limiter) position, and r_0 is the width of the current profile. The parameter λ determines the flatness of the profile, with $\lambda = 1, 2, 4$ giving the peaked, rounded, and flat profiles of Furth, et al.¹⁵

In Figure 1, are shown the radial extents of the 2/1 and 3/2 islands in a peaked profile as a function of q_L for two values of $q(0)$. Since island saturation is due to the existence of a magnetic energy minimum, it is not surprising that shear strongly inhibits large island growth, distortion of a sheared field requiring relatively more energy. It is apparent that dangerously large magnetic islands cannot occur in such a state, and that overlap of the two islands also does not occur. We are interested in values of $q(0)$ in the vicinity of unity, since low values are desirable to obtain high β , the ratio of plasma energy to magnetic field energy, and $q(0)$ is normally restricted from values much below this by the sawtooth oscillation.

A flat profile is much more susceptible to large island development. In Figure 2, are shown the radial extents of the 2/1 and 3/2 islands as a function of q_L for four values of $q(0)$. It is apparent that $q(0) > 1$ and $q_L > 2$ can produce large $m = 2$ islands near the limiter as well as island overlap. Of course,

this single helicity analysis cannot predict the complicated nonlinear behavior to be expected when islands of different helicities overlap. Nevertheless, this analysis can indicate regions of island overlap, since the nonlinear simulations show that until overlap, the islands grow as in the single helicity approximation.

In figure 3, are shown the marginal stability boundaries for the 2/1 mode as well as boundaries for overlap with the 3/2 mode in the plane of q_L and $q(0)$ for various λ . The stability threshold corresponds to the right hand neutral stable point of figs. 5, 6, 7 of Ref. 17. The island width takes on its maximum value near to this threshold, the maximum value being approximately $w = .4$ for $\lambda = 4$ and $w = .2$ for $\lambda = 2$. As seen in Fig. 2, increasing q_L to moderate values only weakly decreases the island size, the main effect being to move the island radially inward. As $q_L \rightarrow \infty$, the island shrinks to zero width and moves into the axis. In addition, we show in Fig. 3 the regions where the 2/1 and 3/2 modes are near the limiter. Within the shaded area, the mode extends to $r = 0.9$ for $\lambda = 4$.

We can compare the predictions of this model both with numerical simulations and with experimental data. First, we consider the results of numerical simulations. Point A on Fig. 3 describes a profile first investigated with a single helicity code,⁹ where it was shown that with $\lambda = 4$, the $m = 2$ mode does indeed develop into a rather large island. A three-dimensional, multi-helicity simulation¹⁰ with $\lambda = 3.24$, showed that the 2/1 island overlapped the 3/2 island, producing explosive growth of

the 3/2 mode. The point is well within the contour for overlap for $\lambda = 3.24$ on Fig. 3. Other numerical runs¹⁰ at point B show overlap with strong destabilization of the 3/2 mode for $\lambda = 3.5$, and weaker destabilization for $\lambda = 2.5$. Runs at point C show no destabilization for $\lambda = 2.25$, and progressively stronger destabilization for $\lambda = 2.5, 3$, and 3.5 . Thus, the occurrence of island overlap and 3/2 destabilization in a full nonlinear simulation can be predicted reasonably well from Fig. 3.

We turn now to the experimental data. Point A is the location of a rather flat profile observed on PLT just preceeding a major disruption,¹ which was the motivation for the numerical simulations discussed previously. As noted, this point falls well within the overlap region provided $\lambda > 3$, but the island does not approach the limiter very closely.

Experiments on several tokamaks indicate that sufficiently small q_L allows disruption free operation^{2,5,6,7,8}. Experiments have been performed on JIPP II to test the possibility of disruption prevention by current density profile control during gas puffing.⁸ The radial temperature profile is measured, and the current density profile and safety factor derived by assuming classical conductivity including the trapped electron correction. The current density profile is controlled by an additional loop voltage applied shortly after the gas puffing. We examine three of the cases reported. Case I is a discharge during which there was gas puffing, but no current profile control. Case II is a case with no gas puffing, but with current profile control, and in Case III, the current profile was controlled following the gas

puffing. Safety factor profiles are given to which we have fit a profile of the form given by Eq. (1) by matching $q(r)$ to their curves on axis, at the limiter, and at the $q = 2$ surface. This method does not reproduce the small irregularities in the profiles, but it gives a quite accurate fit in most cases, and the experimental accuracy of the profile determination probably does not warrant a more exact fit. This method of fitting allows us to depict the history of the discharges on Fig. 3. In Table 1, is given the data for the three cases, as well as the value of λ , the 2/1 island location and saturation width, and whether or not an overlap condition exists. The trajectories of the three cases are shown on Fig. 3.

Experimentally, Case I is observed to experience a sharp drop in ion and electron temperature, and a burst of 2/1 and 3/2 activity and negative voltage spikes shortly after 94 msec, (point 2) and, in fact, the trajectory enters the overlap region. The island is quite far removed from the limiter. Linear stability theory does not give any explanation for this sequence, in fact, the linear Δ' is positive for all three points, but decreasing from 1 to 2 to 3.

Case II experiences a mild but sudden drop in electron temperature accompanied by a burst of poloidal field fluctuations at 90 msec, slightly before point 2. The 2/1 island is rather large at this point and approaches the limiter. Although overlap is possible it seems to be ruled out, since the profile would have to be quite a bit flatter than observed at point 2. The current profile control quickly brings the discharge to point 3

where the island, although close to the limiter, is quite small, and the discharge recovers. Case III, with gas puffing and optimum current profile control, obviously never enters a dangerous region. Two other cases are reported which are similar to Case III. These discharges are stable.

In conclusion, we find from present experimental data that the conditions for the occurrence of a tokamak disruption can be reasonably well understood in terms of magnetic island saturation widths, limiter approach, and $2/1$, $3/2$ overlap conditions. The two experimental major disruptions analyzed (point A and case I) apparently satisfy conditions of island overlap and not those of limiter contact. In particular, Case I of Fig. 3 cannot be understood in terms of $2/1$ limiter contact barring gross errors in the current profile determinations.

We believe that the method outlined in this letter can provide a real time calculation to determine how close an experimental discharge is to disruption and, therefore, might be useful in a control system designed to avoid disruptions. In addition, the method should provide, as more experimental data becomes available, a clear resolution of the necessary and sufficient conditions for disruption.

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TABLE I. Parameters for the three cases of Ref. 7. The numbers refer to points on Fig. 3. Given are the values of q on axis and at the limiter, and the location of the $q = 2$ surface, r_s , as well as the value of λ required to fit the profile, the saturated island width w , and whether or not overlap and limiter proximity conditions exist.

Case	Point	Time (Msec)	$q(0)$	q_1	r_s	λ	w	Overlap	Limiter Proximity
I	1	88	1.0	4.28	0.6	1.4	0.12		
	2	94	1.0	4.45	0.64	2.2	0.17		
	3	98	0.92	4.5	0.65	2.7	0.19	X	
II	1	88	1.0	4.18	0.64	1.75	0.15		
	2	98	1.15	2.82	0.8	2.0	0.17		X
	3	104	1.15	2.47	0.86	1.85	0.07		X
III	1	94	0.96	3.6	0.68	1.45	0.1		
	2	98	0.96	3.0	0.8	2.4	.03		
	3	104	1.0	2.6	0.84	1.7	.02		
	4	108	1.0	2.5	0.88	2.6	0		
	5	118	0.97	2.59	0.86	2.3	0		
	6	128	0.97	2.82	0.84	4.0	0		
	7	148	1.04	3.2	0.76	2.25	0.15		

(PPPL-802134)

Fig. 1. The radial extent of the 2/1 and 3/2 islands as a function of q_L , the safety factor at the limiter, for two values of $q(0)$. The profile is the peaked model, $\lambda = 1$, and island overlap does not occur.

(PPPL-802133)

Fig. 2. The radial extent of the 2/1 and 3/2 islands with a flat profile, $\lambda = 4$, as a function of q_L for four values of $q(0)$. Large island states and overlap occur.

(PPPL-802142)

Fig. 3. Regions of 2/1 and 3/2 overlap in the plane of q_L and $q(0)$. Also shown are the marginal stability boundaries for the 2/1 mode for $\lambda = 2, 4$. The shaded regions are zones in which the modes are close to limiter contact, the limit of the zone defined by the island extending to $r = 0.9$ for $\lambda = 4$. These zones are somewhat modified for different λ .