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Report

TOKAMAK DISRUPTIONS

J. A. WESSON
A. SYKES
M. F. TURNER

CULHAM LABORATORY
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TOKAMAK DISRUPTIONS

J.A. Wesson, A. Sykes and M.F. Turner
Culham Laboratory, Abingdon, Oxon., UK
(Euratom/UKAEA Fusion Association)

Abstract

An explanation is given for the occurrence of tokamak disruptions. Under normal conditions the tearing instability is self-stabilising through its reduction of the destabilising current gradient and a saturated state can then exist. However under certain conditions further growth of the instability is itself destabilising and a disruption results. The transition to disruption has the form of a catastrophe.

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In looking for an explanation of tokamak disruptions[1] it is necessary to examine various aspects of the problem. Firstly there is the question of what pre-existing conditions give rise to a disruption, for example, high current and high density. Secondly there is the need to understand the process of the disruption, that is the detailed way in which the disruption develops. Finally there is a requirement to explain why a disruption occurs, particularly how it can occur with no perceptible change in the pre-existing conditions. We here address this last issue and propose an explanation in which the disruption takes the form of a catastrophe.

Disruptions often occur in tokamaks after a long period of almost constant conditions during which steady $m = 2$ magnetic oscillations are observed. The first sign of disruption is a rapid growth in these oscillations. The oscillations are due to an $m = 2$ tearing mode which, during the steady period, has a saturated magnetic island at the $q = 2$ surface. This state may be regarded as one in which the free energy arising from the destabilising current gradient has been relaxed by the formation of the island. In order to explain the disruption we must make an examination of the factors governing the size of the island. We shall find that, whereas under non-disruptive conditions island growth is a stabilising effect, beyond a critical condition island growth is destabilising and disruption occurs. Slightly to one side of this condition a steady saturated island exists but an arbitrarily small change leads to disruptive growth.

The destabilising force for the tearing modes arises from the negative current gradient at radii inside that of the resonant surface ($r = r_s$). In linear theory the measure of instability is obtained by solving the equation[2]

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\psi}{dr}\right) - \frac{m^2}{r^2}\psi - \frac{dj_o/dr}{B_{\theta o}(1 - nq/m)}\psi = 0 \qquad (1)$$

where ψ is the perturbed flux function $(\propto r B_r)$ for a mode having poloidal and toroidal mode numbers m and n, j_o and $B_{\theta o}$ are the equilibrium axial current density and poloidal magnetic field and q is the safety factor. Solutions of the equation in the regions $r < r_s$ and $r > r_s$ are then used to calculate

$$\Delta' = \frac{\psi'}{\psi}\Bigg|_{r_s - \varepsilon}^{r_s + \varepsilon} \qquad \varepsilon \to 0$$

If $\Delta' > 0$ an island forms. For small islands an estimate of the island saturation width, w_s, is given by

$$\Delta'(w_s) = 0$$

where

$$\Delta'(w) = \frac{\psi'}{\psi}\Bigg|_{r_s - w/2}^{r_s + w/2} \qquad (2)$$

A more complete calculation leads to a correction[3] $\Delta'(w) = \alpha w$ but this is not essential for understanding the basic behaviour. A typical graph of $\Delta'(w)$, showing how it determines w_s is shown in figure 1.

For larger islands the non-linear effect of the island on the equilibrium becomes important. This is included in the analysis by writing equation (1) in the form

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\psi}{dr}\right) - \frac{m^2}{r^2}\psi - J(w)\psi = 0\ .$$

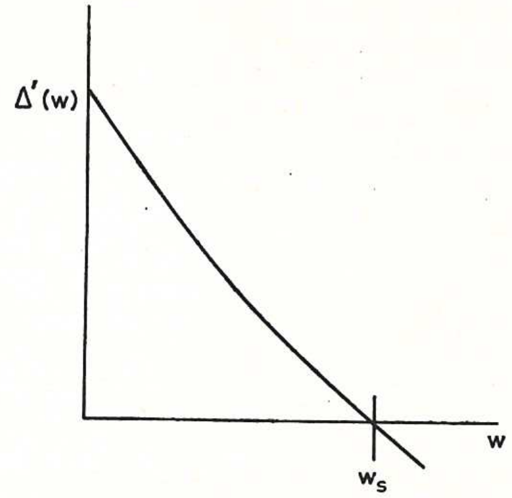

Fig.1 Graph of $\Delta'(w)$ showing how the saturation island width w_s is determined. The island grows until $\Delta'(w) = 0$.

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where

$$J(w) = \frac{dj/dr}{B_\theta(1 - nq/m)}$$

the variables onthe right hand side now being the equilibrium quantities consistent with the presence of the island. The island size is still given by $\Delta'(w_s) = 0$ but there are now two coupled effects of varying w. One is the effect of varying the position $(r = r_s \pm w/2)$ at which ψ'/ψ is calculated, the other is the change in the function $J(w)$. For clarity we shall designate the Δ' calculated including both effects by the symbol Δ^*. Under conditions of interest in the present context $\Delta^*(w)$ takes the form shown in figure 2. There are then two possible non-linear equilibria, with island widths w_{s1} and w_{s2}, their stability being indicated by the arrows. If the imposed conditions are varied by,

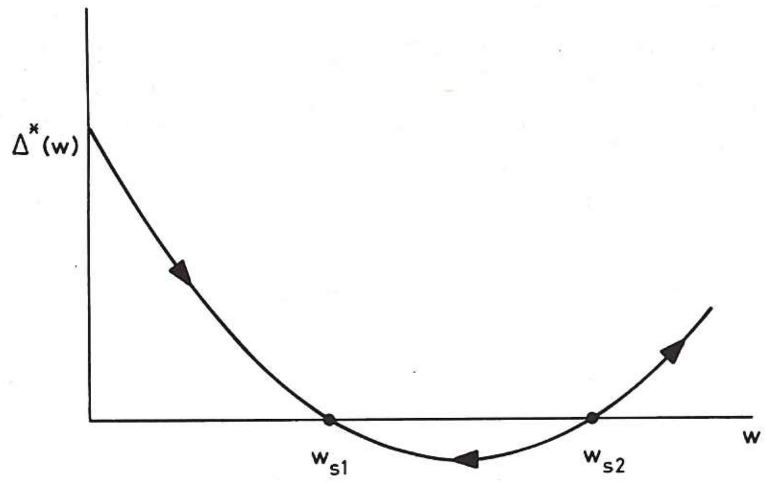

Fig.2 Graph of Δ*(w) showing how inclusion of the self-consistent modification of the configuration changes the calculation of w_s. There are now two solutions, the stable w_{s1} and unstable w_{s2}.

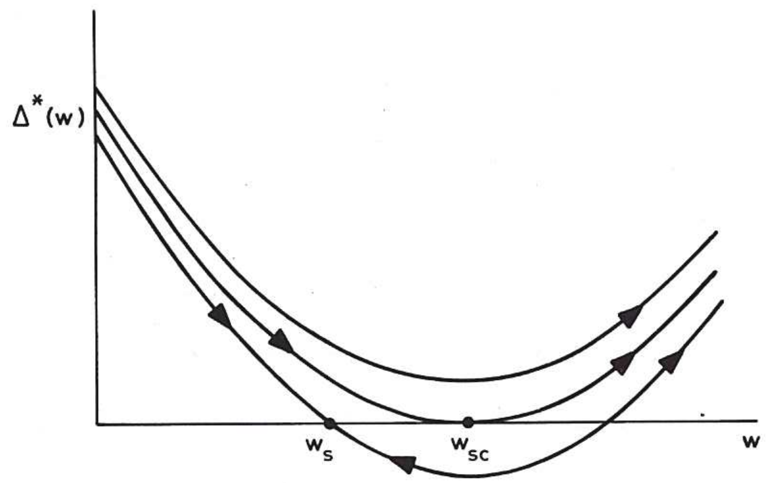

Fig.3 Graphs of Δ*(w) showing how the saturated island width, w_s, adjusts until the catastrophe point, w_{sc}, is reached. No steady solutions then exist and w grows disruptively.

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say, an increase in the total current or amount of plasma impurity, there is a set of such curves as illustrated in figure 3.

If the conditions are slowly changed to produce a larger island, the point w_s moves across adiabatically. If, however, the critical width w_{sc} is reached, the island grows spontaneously and a disruption occurs.

There are two basic factors which lead to this situation and these are illustrated in figure 4. The dashed line shows the radial profile of the current density which would occur in the absence of instability and impurities. The first factor leading to disruption is the effect of the cooling of the island region through contact of the island with the limiter or cold plasma in the outer region. As seen from the figure this displaces current from the island region to enhance the destabilising

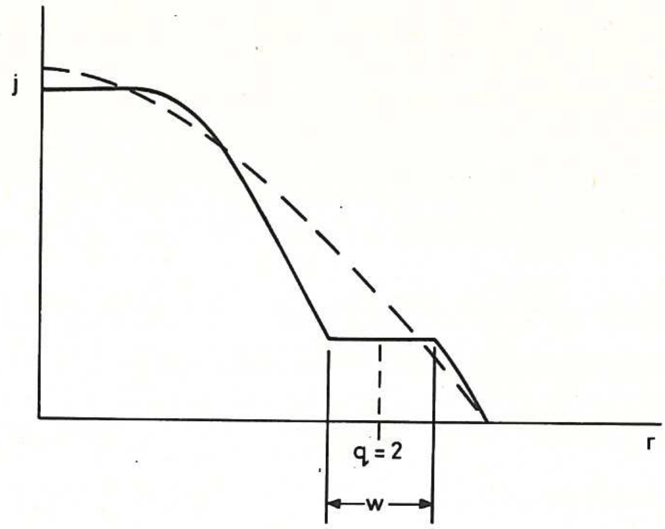

Fig.4 Graph of j(r) showing how a limitation of j around the axis together with the removal of current from the region of the cooled island leads to a non-linearly destabilising current gradient.

current gradient at inner radii. The second factor is the restriction of the current density around the axis either by mhd instability[4] or by increased resistivity due to impurities. This prevents the current from concentrating around the axis and again enhances the destabilising current gradient as seen from the figure.

This theory supports and clarifies the calculations of self-consistent "torn" equilibria carried out by Sykes and Wesson[5]. In these calculations it was found that under conditions associated with disruptions no equilibria could be found.

As an example of the theory, calculations of $\Delta^*(w)$ and w_s have been carried out for disruptions induced by low q_a, q_a being the surface value of q. The model includes limitation of the value of q at the axis by mhd instability and the determination of the resistivity profile by a simple transport model. The details are given in ref. 6. Plots of $\Delta^*(w)$ are given in figure 5a and the resulting island widths are plotted against q_a^{-1} in figure 5b. While the theory is not accurate for the large island widths obtained under conditions of disruption, the catastrophe nature of the disruption is made apparent.

The process of disruption has been studied in a number of calculations. In a simulation by Sykes et al.[7,8] the $m = 2$ mode was followed through to a disruption and the resulting loss of confinement demonstrated. A calculation including many modes was carried out by Carreras et al.[9] It was found that the $m = 2$ mode grew less strongly but the combined effect of all the modes covered a somewhat larger part of the plasma than when the $m = 2$ mode alone was allowed. It seems likely that the details of the process are not important. The essential point is that under disruptive conditions the relaxation of the free energy associated with the current gradient leads to a <u>more</u>

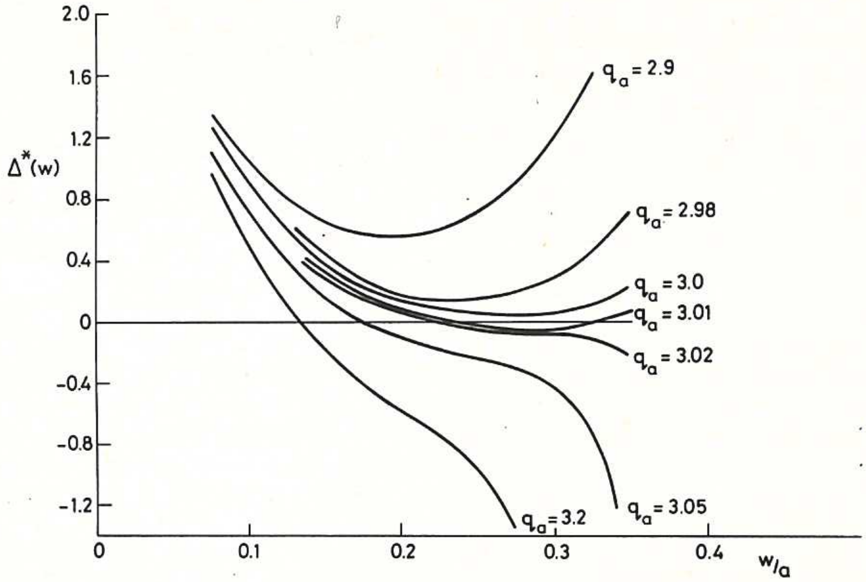

Fig.5(a) Computed graphs of $\Delta^*(w)$ for a number of values of q_a.

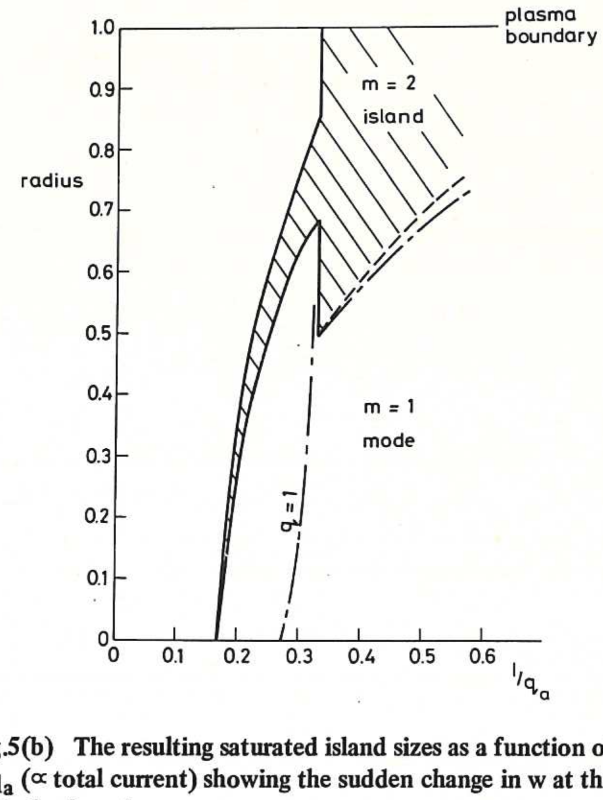

Fig.5(b) The resulting saturated island sizes as a function of $1/q_a$ ($\propto$ total current) showing the sudden change in w at the critical value of q_a.

unstable configuration.

It should be noted that in this model the island forms at early times and changes slowly with the determining conditions. The size of the island at disruption need not necessarily be large and the level of observed fluctuation could therefore be small.

In summary we can say that certain experimental conditions are found to lead to disruption; these are principally low q_a and high plasma density. The disruption can appear without a perceptible change in the pre-existing conditions. The first sign of the disruption is a rapid growth in the $m = 2$ mode. This is explained by the loss of non-linear equilibrium, induced by an interaction between the $m = 2$ island and the destabilising current gradient. Under non-disruptive conditions a saturated island exists. As the conditions are made more severe, the island size increases adiabatically. At a critical point a catastrophe occurs and further island growth is destabilising. This is proposed as the basic cause of disruptions.

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