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MHD ACTIVITY ON JET

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ABSTRACT

A survey of the MHD activity observed in both the ohmic and early radio frequency heated phases of the JET project is presented. The activity or its absence, during the initial current rise phase, flat top and current fall phase has been investigated. A study of disruptions both at the density limit and at low q has also been made. Some comparisons with linear and non-linear 2D resistive instability calculations are presented. During the initial current rise phase mode activity can be quite complex. During the flat top phase the activity can be absent even at low q. Disruptions occur with primarily m=2 precursors which slow down whilst growing and lock before the disruption. Internal disruptions (sawteeth) are observed on the internal coils. Modes with more than 1 helicity are usually present. At least 2 toroidal mode numbers are present and for a single toroidal mode number, the presence of current perturbations on more than 1 rational q surface is deduced.

INTRODUCTION

Although the MHD activity in normal stable tokamak operation is low the evolution of the current distribution can lead to either stationary or slowly growing magnetic perturbations and these may lead to the sudden loss of confinement associated with a disruption. The disruptive behaviour is of particular interest physically in so far as it involves reconnection and turbulence but it is also a cause for concern on large tokamaks where damage can occur if there are many disruptions or if they are rapid.

Minor and major disruptions are observed to occur on JET throughout the full evolution of the current pulse. Most of these are associated with the plasma evolving towards the density limit which may vary somewhat depending on the purity of the plasma but a few discharges do evolve to the q limit.

It is of particular interest to compare the MHD activity and disruption behaviour on the JET device with medium and smaller tokamaks, particularly because of the scaling in dimension, the large magnetic Reynolds number $S \sim 10^8$ and that JET is non-circular and of tight aspect ratio. All of these effects are expected to have a profound influence on the mode behaviour and possibly on the disruption characteristics.

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In each octant there are 18 internal coils which measure the tangential component of the field, located at positions as shown in Figure 1. Also on each octant there are 14 saddle coils which have been used to measure the normal component of the magnetic field. The internal coils are shielded by an inconel tube and have a frequency response approaching 10 KHz. The external saddle coils are limited by the penetration time through the inconel vacuum vessel which is ~ 5ms. Figure 1 shows a typical elliptical equilibrium calculated from the measured magnetic fields and fluxes with these coils.

In addition to single coil measurements, MHD signals, primarily sensitive to the m=2,n=1 mode are provided which are made up of 4 coils in one octant and 4 coils in the opposite octant, which are chosen to give the optimum sensitivity to the m=2 mode for a full aperture D-shaped plasma. This signal which is first rectified and smoothed and then slow sampled is available throughout the full discharge evolution. Unfortunately due to the long pulse length on JET (~ 10s) only a short window, typically ~ 400ms can be sampled with a sufficiently large number of individual coils to make poloidal, m, and toroidal, n, mode number determination with any precision. The slow sampled MHD signals are also available for n=1 and n=2 mode activity. Figure 2 shows the signal from one of the composite MHD coil systems. The activity conveniently breaks up into 4 phases - initial current rise phase, characterised usually by a substantial signal from the coil combination, a second phase associated with the slow current rise which often produces additional activity - the flat top phase characterised by sawtooth activity and finally a current decay phase which in the early ohmic phases of JET operation was often associated with a disruption. To study disruptions a disruption trigger which is derived from the plasma current signal is used.

MODE DETERMINATION FROM AMPLITUDE AND PHASE

The signals can be analysed as a super-position of several modes:

$$\delta B_\theta(r,\theta,\phi) = \Sigma \delta B_{mn}(r) e^{i(\omega_{mn}t+m\theta-n\phi+\chi_{mn})} \qquad (1)$$

Where ω_{mn}, χ_{mn}, δB_{mn} are respectively the angular frequency, phase and amplitude of the oscillations, r is the minor radius, θ and ϕ are poloidal and toroidal angles. Such perturbations are usually the result of tearing modes arising from a resonance surface $q(r_s)= m/n$ inside the plasma. Outside the plasma such perturbations in cylindrical geometry in the presence of a conducting wall would behave as $\delta B_{mn}(r) \propto (r^{m-1}+r_w{}^{2m}/r^{m+1})$ where r_w is the radius of the conducting wall. Given the mode rotation of about 1 kHz the vacuum vessel acts as a good conducting wall. This expression is a good approximation even for a tight aspect ratio device such as JET when the plasmas are close to circular as they are in the initial current rise phase. Equation (1) should include toroidal, non-circular and plasma displacement effects. Toroidal effects [1] can be included by defining a new poloidal angle

$$\theta^* = \theta - \lambda\sin\theta,\ \lambda = (r/R)(1+\ell_i/2+\beta_\theta) \tag{2}$$

For full aperture plasmas on JET this toroidal correction is quite substantial. We have used a variety of equilibria obtained from magnetic analysis on JET for various elongations to evaluate the transformation from flux co-ordinates in the plasma to the coil co-ordinates at the wall. Quite a good fit to these equilibria and to those used in the stability calculations is

$$\theta^* = \theta - 0.52\sin\theta - 0.21\sin2\theta + 0.09\sin3\theta \tag{3}$$

This introduces a large phase shift away from that we would expect in cylindrical geometry. This effect is shown in Fig.3. As can be seen from the experimental phase plots for JET which do determine the principle poloidal mode number at the wall, the full effect is not seen though a significant $\sin\theta$ term is evident for m=3. The fact that the phase asymmetry effect appears to be so small in all cases for JET mode activity, indicates that there are substantial side-band perturbations to cancel out these effects. For example Fig.3 implies that for m=2 there is ~ 40% m=1 and m=3 as well. This indicates that there are significant tearing mode perturbations on other rational surfaces as predicted by the 2D resistive instability calculations. A knowledge of the side-band strength is particularly important both in determining the perturbation to the magnetic surfaces caused by the development of the resistive instabilities and it may permit other information to be gained in detail about the current distribution.

For plasmas which are close to circular we have found it possible to determine the principle mode number m simply from range effects conveyed by $\delta B(r)$. Since the coils are at different radii from the resonant surface then if we allow for the conducting wall we find that $\frac{\delta B(r_1)}{\delta B(r_2)} \sim \left(\frac{r_1}{r_2}\right)^m$ where r_1 and r_2 are the distances from the centre of the resonant flux surface to the coils. The amplitude variation with poloidal angle as shown in Fig.4 is also useful information in revealing the strength and size of the relevant side-band harmonics. Thus an m=3 or 1 side-band to m=2 which is positive will make the mode balloon and this is what is normally observed, however at low q as Fig.4 curve (a) shows, sometimes there is no ballooning. Thus we can determine the poloidal mode content both from the amplitude and phase variations by fourier transforming in θ^*.

TEARING MODES

If the resonant radius is inside the current carrying plasma column then we are concerned with growing and saturated tearing modes which are sensitive to the current gradient in that region and to other resonant surfaces depending on the shape and aspect ratio of the device. There are very specific predictions for tearing modes in cylindrical geometry for example tearing modes with high m have a well known stability criteria [2] and these are confirmed by initial value resistive instability calculations [3]. In general it is difficult to destabilise modes with $m \gtrsim 5$ apart from profiles with very steep edge gradients. Tearing mode calculations including toroidal effects and shaping in some cases lead to stabilising and in some cases to destabilising effects so that cylindrical calculations maybe substantially in error particularly for JET [4,5]. In addition at high values of the magnetic Reynolds number, S, as occur on JET, and significant values of poloidal beta there are strong stabilising effects[6], which for a beta poloidal of about 0.2 and $S \sim 10^9$ could stabilise the m=2 tearing mode. Mode coupling is an important feature of tearing mode calculations for JET. It is possible to calculate Δ' exactly for on-axis resonant m=2, m=3, m=4 tearing modes. For m=3 with $\Delta'=2.46$, toroidal effects associated with the JET aspect ratio are sufficient to stabilise this mode. They are not strong enough to fully stabilise the m=2 mode.[7]

Solving the coupled tearing mode problem in toroidal geometry in particular with non-circular effects is difficult. However for circular cross-sections in toroidal geometry it is possible for the case with two resonant surfaces present e.g. that associated with q=2 and q=3, to show that if the m=3 perturbation at the q=3 surface has $\Delta_3' < 0$ then it can stabilise the m=2 tearing mode with $\Delta_2' > 0$ if the sum of $\Delta_2' + \Delta_3'$ is negative and if $|\Delta_2' \cdot \Delta_3'|$ is less than 4 for JET[8]. To study these effects in more detail we have used both the FAR code [9] from Oak Ridge and the RESTOR code [10] both of which are incompressible and do not assume tokamak ordering. We have used the measured equilibria as input to the codes. In general they predict a substantial spectrum of modes with n=1 and growth times of a few ms. The mode spectrum which typically has side-bands of $\sim$ 50% of the principle harmonic, is confirmed by both the phase and amplitude measurements on JET i.e. strong coupling occurs with perturbed currents at several different resonant surfaces. However, the evolution of the plasma appears to be more stable than these calculations would predict. The mixed mode content is sufficient to explain the mixed mode behaviour and the amplitude as seen on JET. It is quite conceivable that other two-fluid effects such as finite

Larmor radius terms may play a significant role in stabilising the potential instabilities and only if the current distribution becomes strongly unstable in the purely resistive limit i.e. with strong edge gradients, do the modes appear. From these calculations it is possible to compare the primary harmonic and the side band harmonics with those measured experimentally and then to deduce the magnetic island sizes on the different rational surfaces. Such calculations do indicate island overlap in many cases before disruption occurs.

MHD ACTIVITY DURING CURRENT START UP

During the initial phase the behaviour can be quite complex and a number of situations can be distinguished. Under some circumstances it is possible for a very rapid peaking of the current profile to occur combined with an absence of the usual sequence of descending m=q instabilities during the current start up phase. During this first second of the discharge disruptions may occur which are very similar in character to the terminal major disruptions, however the most important difference is that they are not terminal in this case. Mode locking may or may not occur depending on the perturbation amplitude and reconnection and relaxation of the column is observed. This is accompanied by a rapid energy flux to the plasma edge. The descending sequence in poloidal mode number does appear in the slow current rise to flat top under some conditions, in particular if the current ramp rate is high enough. If such modes reach high amplitudes the rotation which is in the electron diamagnetic drift direction or antiparallel to the plasma current, ceases.

Four types of start up discharge can be distinguished from the MHD activity; in each case the poloidal mode number is deduced either by amplitude or phase measurements. It must be borne in mind that the plasma usually starts ~ circular and close to the outer limiter. As the current increases so the aperture and elongation increase. During the start up phase the dominant toroidal mode number is n=1 in all cases, and the mode frequencies, typically 700-1500Hz.

Type A MHD signature very quiet with only m=4, 5 or 6 and sometimes no detectable signal. The discharge start up is successful. The frequency of such discharges is rare. Broad electron temperature profiles, sometimes slightly hollow, are observed in the electron cyclotron emission diagnostic, occasionally with wings. The sawteeth usually start late $\gtrsim$ 1s.

Type B The signature in this case is a larger amplitude m=3 and 4 mode with weak reconnections and a discharge start up which is successful. Such behaviour is fairly common and profiles are not very different from those of type A. Sawteeth may start as early as .5 s.

Type C Large amplitude m=2, 3 and 4 modes sometimes with strong reconnections and hard disruptions. The mode may lock without disruption, the discharge start up is successful and the frequency is rather less common than B. The temperature profile is somewhat variable including markedly hollow ones and sawteeth can be as early as those in B.

Type D Large amplitude modes as in C but with repetitive disruptions and the discharge start up fails. These are very rare now in JET. In such discharges the density remains close to the JET high density limit and the temperature remains low.

Figures 5, 6 and 7 show examples of type A and C. The most remarkable feature is that modes with primarily m=2,n=1 are seen when q at the limiter > 10 and the current is increasing. The peakedness of the current profile is confirmed by the early appearance of sawteeth indicating $q_0 \sim 1$.

Figure 5 shows a case with m=4 activity and late appearance of sawteeth (> 1s). The high m value is indicated by the rapid attenuation of the signal with distance. In this case the mode amplitude reaches ~ 1% and the island at the q=4 surface is ~ 9cm. This perturbation level is apparently not large enough to produce any reconnection. Figure 6 (and 7) shows a case C start up where there is an initial fairly strong disruption involving the m=2 mode at 40.21s (and 40.18s) which reaches a perturbation level of some 3% without locking. The plasma reconnects, shifts inwards and is followed immediately by a burst of m=4 activity (see also Fig.7 at 40.42s) indicating that the current distribution has expanded out to the q=4 surface. This then decays and is followed by bursts of activity with m=3 which reaches an amplitude of 3% and reconnection occurs. Soft disruptions occur repeatedly and the current distribution contracts further with the amplitude of the m=3 mode falling while the m=2 rises and sawtooth activity starts. The m=2 activity slows and builds up to a perturbation level of about 1% and then locks at 40.62s. The mode locking does not lead to disruption but presumably decays away. Figure 7 shows a case where mode locking occurs at 40.41s before disruption on the current rise. Discharges of type D essentially reach the first strong m=2 disruption at 40.2s and then expand and contract again and fail to get out of this cycle. From the rapid inward displacement of the plasma column associated with a decrease in inductance it is possible to estimate the expansion of the current distribution on reconnection. $\Delta \ell_i \sim$ 0.1-0.15, this is sufficient to expand the current carrying column, so that the current gradient moves from the q=2 surface to q=4 and would then be expected to produce m=4 activity, as observed.

The soft disruptions are clearly visible on the signals from the soft x-ray detectors (Figs 6 & 7). In the early phases of the discharge the plasma current is relatively low (~ 400 kA) and the activity is almost all n=1 with little evidence of any activity with n=2 except possibly at reconnection. The m=3 disruptions associated with the initial current rise are very similar to those observed on the TOSCA device. In that case probe measurements identified the activity as an m=3 tearing mode. It is possible for the perturbation with m=3 to have toroidal side bands which lead to reconnection via island overlap and expansion of the current carrying column.

Attempts to correlate the observed MHD behaviour with ECE measurements of the temperature profile are in reasonable agreement but there is probably a substantial variation of the electric field and Z_{eff} with radius during this phase. From our observations, it is difficult to make comparisons with the predicted double tearing modes [3], associated with hollow current profiles which may be present during the current rise phase, nevertheless we see little or no evidence for reconnection occurring at high values of m which could be correlated with two resonant q surfaces. This could be interpreted as a broad profile with a steep gradient which leads to large amplitude mode activity.

It should be noted that during this current rise phase at low I_p, energy quenches can occur but without current termination. This is probably associated with the fact that the feedback system is able to handle the large shift in plasma position associated with the drop in plasma inductance.

INSTABILITIES ON THE SLOW CURRENT RISE

A programmed rate of current rise ~ 0.5MA/s is used to reach the desired flat top after the initial rapid current rise. Often there is no activity in the slow rise. Occasionally there are small bursts of oscillations when q limiter is near integral values. For q~4 the m=4 mode has been identified. In such a case the I was 0.7MA/s. The field perturbation level reaches about 1% and the mode locks when the perturbation is ~ 10 gauss. The m=4 n=1 activity is accompanied by n=2 activity as well. It would seem that this behaviour is in reasonable accord with tearing mode stability predictions. Even though the magnetic island size in this case is deduced to be ~ 10 cm which should interact with the limiter, there is no clear evidence for this from the evolution of the discharge. No clear link has been found between the high levels of MHD activity in the early period of the discharge and increased impurity concentration Z_{eff}.

MHD ACTIVITY AND SAWTOOTH OSCILLATIONS

The sawtooth activity is clearly visible superimposed on the MHD activity as shown in Fig.8. The reconnection phase is visible as an enhancement in this particular case in the m=2,n=1 activity by a factor of ~ 3 for a duration of 2ms. The sawtooth period in this case is ~ 40ms, though sometimes double sawteeth are observed which can give periods in excess of 100ms. These are also seen on the MHD coils. The amplitude of the poloidal field fluctuations at the q=2 surface is 3 x 10^{-4} giving an island size of ~ 1cm.

This type of activity is also seen in discharges which are close to producing continuous m=3,n=1 activity. For example in a discharge with 2.9 MA, q_ϕ ~ 4.3, the sawtooth post-reconnection bursts have a frequency of ~ 1 KHz and may last for 2 or 3 periods with m=3,n=1 Fig.9. No coherent mode activity is evident between the sawtooth reconnection phases and a drop in the cyclotron emission signal indicates that reconnection takes place shortly after the rapid growth (τ <60μs) of this mode. 2D resistive instability, calculations show that for q(0)$\lesssim$1, edge coils will see the growth of the internal m=1, n=1 mode as the field produced by the perturbed current on the resonant surface in the plasma close to the coil, via toroidal coupling. No other precursor is evident before the sawtooth reconnection. Extensive investigations combining the coils both toroidally and poloidally to look for a precursor mode at a low level or by integrating to look for a locked internal mode which should be visible externally through its toroidal side-bands, has indicated no detectable MHD activity before reconnection on ohmic discharges. The mode activity often has a very strong ballooning character. It would seem to imply that the first two sidebands are almost equal in strength to cancel the primary perturbation on the inside.

In many discharges the reconnection phase may be visible only as a single spike associated with rapid mode growth and similar to that seen sometimes for 'soft' disruptions with m=2 n=1. This rapidly growing mode is sometimes seen on the e.c.e. diagnostic preceding the drop in temperature on a timescale of ~ 100μs. The size of the perturbation is typically ~ 10^{-4} and decreases as q increases. That is presumably because the q=1 surface moves further away from the detecting coils and the growth which couples the m=1 mode toroidally to the other resonant surfaces at high q or m produces a perturbation which is small and decays too rapidly to be visible on the coils at the boundary. Nevertheless it is interesting that the rapid growth phase at the sawtooth is visible in this way through toroidal coupling. This type of activity is seen in smaller tokamaks (eg CLEO) particularly when they operate at low q $\gtrsim$ 2 and at high β associated with additional heating. These spikes also occur on JET, though in a weaker form on the partial reconnection associated with the double sawteeth.

OBSERVATION OF MODES WITH DIFFERENT n

A number of discharges close to the density limit exhibit an irregular form of oscillatory mode activity, Fig.10. This is for a discharge during which the current is decaying and finally disrupts at 50.686s with I_p = 1.1MA and b/a = 1.5, q_ϕ = 8. The n=2 component has twice the frequency of the n=1 consistent with purely toroidal rotation at speeds up to 3 x 10^4m/s. This behaviour confirms that the low amplitude eigenmodes have a single dominant n in the tight shaped plasmas on JET. The n=2 component is triggered at a critical level of the n=1 which increases from ~ 0.05% to 0.08% of B_θ and saturation occurs with the δB (n=2) ~ 25% δB (n=1). The two modes then decay together, the frequency falls slowly and the maximum amplitude increases with time. Phase measurements indicate that the mode is primarily m=2,n=1 with significant 3 and 1 sidebands. Phase measurements of the n=2 activity indicate an m value of between 3-4 and because of the toroidal effects on the phase and the temporal behaviour of the mode, this is taken to imply a distinct mode with m=3,n=2. The relative phase is that expected from simple nonlinear effects, ie the n=2 component has an O point at the outboard O point of the parent 2,1 island. In the final oscillatory mode burst the n=2 activity saturates at about 0.05% B_θ while the n=1 part continues to grow exponentially with a growth time of ~ 10ms until mode locking occurs in this case at an amplitude of ~ 0.7% of B_θ. The modulations are not directly correlated with the sawtooth which has a period of about 30ms continuously during most of the figure.

Not all discharges are as those shown in Fig.10, often the n=1 and 2 components grow together with the ratio n=2:n=1 ~ 25%. A particular case has been observed when a radiation dominated layer moves in from the limiter where the n=2 mode is identified primarily as m=3 with a larger out/in amplitude ratio (~ 3) than the m=2 signal which is about 2. The 2,1 and 3,2 islands are estimated to be similar in size and overlap may occur even before mode locking but in this case no contact with the limiter is expected. The n=2 component saturates while the n=1 grows exponentially (τ_G ~ 10ms) until locking when the growth becomes approximately linear though a dependence as slow as $t^{\frac{1}{2}}$ cannot be excluded. The electron temperature profile narrows and flattens before disruption, seeming to imply a steepening of the gradients near the edge of the plasma which from the code calculations would imply an increasingly unstable plasma with reconnection and disruption becoming more probable.

n=2 signals have also been observed when m=4,n=1 modes are excited in a final phase of the current rise and in this case the poloidal mode number > 5. Oscillations stimulated after some delay with m=3, n=1, by the appearance of a radiation dominated region at the edge of the plasma (Marfe) are also observed to have n=2 components again ~ 25% of the n=1.

DENSITY LIMIT DISRUPTIONS

These arise in the current rise, the flat top phase and on the current run down. Before discharge cleaning was effective on JET disruptions were highly probable on the current run down phase when the density decay would be slower than the current decay. With improved conditioning such disruptions have tended to disappear. The disruptions can be severe eg Fig.11 shows a strong rise in the m=2,n=1 signal to a perturbation level of ~ 1½% when mode locking occurs. There is then a delay of between 20 - 100 ms before disruption. This delay time is found to be a linear function of the plasma current, above 400kA. Below 400kA mode locking is not observed to occur. This observation implies that mode locking is coupled to a critical perturbation amplitude ~ 10G at the wall.

The current can decrease to zero in 25-30ms giving an $\dot{I}$ of 10^8A/s which is similar to that observed on the small TOSCA device (2 x 10^8A/s) on TFR (0.6 x 10^8 A/s), and on TFTR (~ 10^8 A/s).

A number of disruptions have been examined in considerable detail. It is important to note that not all disruptions display oscillating mode activity before disruption. In these cases multipole moment analysis by Alladio and Criscanti [11] has shown that significant helical distortion of the plasma column has occurred early in the evolution of the discharge ie the locked mode phase may last for seconds and may induce a number of soft disruptions before the column finally disrupts. On smaller tokamaks which are axisymmetric, mode locking is not normally observed eg on TOSCA, CLEO, TFR. Mode locking can be induced on such tokamaks by introducing a non-symmetric perturbation eg a resonant helical field as on the TOSCA device, the bundle divertor on DITE has a similar effect. It should be noted that mode locking is observed on TEXT where no such perturbation is applied. A possibility is that the mode locking is linked to a specific carbon limiter and distortion of the waveform certainly indicates locking to a local inhomogeneity. The non-zero resistivity of the vacuum vessel wall will be such as to attenuate the radial field producing an image current. This will lead to a net force by the wall on a moving magnetic perturbation and this will act to slow down the electron fluid as the frequency of the mode and the wall time constant are not very different.

Figure 12 shows the mode behaviour shortly before a density limit disruption. I/N ~ 1.3 x 10^{-14}Am, a value very similar to the density limit observed on many medium and small tokamaks. Following the last reconnection phase of the sawtooth the mode activity is primarily m=2,n=1 and increases exponentially with a growth time of ~ 10ms (on a small tokamak this phase before disruption is also exponential but with a much smaller growth time eg ~ 50μs on TOSCA). This growth time is comparable to that of the vacuum vessel but also to the hybrid timescale associated with a resistive mode for an unstable current distribution such as that given in the 2D resistive code calculations. The Figure shows that the amplitude reaches ~ 1% at the q=2 surface and the mode locks, the island size is then ~ 14cm. The toroidal side band with m=3, n=1 and the n=2 mode could well give rise to islands of sufficient size for overlap to occur at this point. After mode locking occurs the amplitude continues to grow. Integration of both the tangential field coil signals and the saddle coils, external to the vacuum vessel, show that the mode grows almost linearly as shown in the Figure, though sometimes the time dependence is closer to $t^{1/2}$ for the growth of the n=1 mode. In this particular discharge the amplitude increases from ~ 1% to ~ 3% when the column disrupts. During this locked mode phase both soft X-rays and electron cyclotron emission diagnostics indicate that some redistribution of heat ie reconnection takes place. There is relatively little growth of n=2 activity during this phase. The poloidal mode number is primarily m=2 in the locked mode phase but it does have substantial side bands with m=1, 3 and 4. In many of these density limit disruptions the column is detached and remote from the limiter and often possesses a radiating edge region so that no contact with the limiter is possible. Examination of the evolution of the inductance and poloidal β during this phase shows very little change. It should be noted that a current distribution which broadens in the core but contracts at the edge, approximately conserves ℓ_i so it is not surprising that the evolution towards a more unstable current distribution is not detectable in the time evolution of the self inductance. The break up of a column and the energy quench is often, though not always, accompanied by very rapid growth of a mode whose m number again appears to be principally 2 and toroidally mode number n=1 on a timescale < 100μs. The energy quench occurs in ~ 1 ms, the column moves rapidly inwards and the current increases. There may be sustained MHD activity for many ms at high amplitude level and the column may partially recover before going through several disruptions as the current runs down. Before these disruptions there is good evidence from cyclotron emission diagnostics that there is a decrease of the temperature in the core of the plasma and a contraction of the edge zone on a timescale of ~ 1 s.

DISCHARGES AT LOW q

As shown in Fig.13 the amplitude of the MHD activity in elongated plasmas in the early phases of ohmic operation in JET increased when $q_\psi < 4$ and for the circular plasmas this increase in activity occurred for $q_\psi \lesssim 3.5$ [12]. However after extensive conditioning of the discharge by carbonisation, discharge and glow cleaning, this rise in activity has decreased substantially and discharges can be free from coherent modes with $\delta B/B_\theta < 3\ 10^{-5}$ for $q_\psi \gtrsim 2.3$. No pronounced activity has been detected at $q_\psi \sim 3$. This is in contrast to observations on other tokamaks at lower value of S and of circular cross-section.

Figure 14 shows a set of waveforms for a low q disruption on JET [13] which in this case is somewhat below the density limit. The oscillatory period of the mode activity is very brief ~ 10ms. The growth in both oscillating and locked periods is ~ exponential with a growth time of 3ms. During the oscillatory phase there is some 25% n=2 mode growth. This behaviour should be compared with the linear growth after locking which is observed at high q before density limit disruptions and when the oscillatory mode grows exponentially with a growth time of ~ 10ms. In this case q_ψ is ~ 2.3 at disruption and the mode structure is primarily m=2,n=1 with an in-out amplitude ratio of the locked mode close to unity and similar to that shown in Fig.4. This seems to imply an approximately equal mix of m=3,n=1 and m=1,n=1 of appropriate sign relative to the m=2 mode. This is in accord with the resistive MHD code predictions. When the mode perturbation level reaches about 2% additional structure appears on the rate of change of tangential field coil signal and at this change (47.245s) the electron cyclotron emission from the central region falls which is not as in the normal sawtooth reconnection. The 2,1 island is predicted to overlap the limiter but the perturbed field continues to grow and reaches a maximum of some 290G (6% B_θ) just before disruption. The energy quench as revealed by the electron cyclotron emission signal (major radius ~ 3.3m) is rapid (< 1ms). As in previous disruptions mode locking occurs at a perturbation level of about 10G. The n=2 activity does not continue to rise which would seem to indicate that no further overlap with an island at the q=1.5 surface is indicated. Though a significant m=1 perturbation is indicated, the last sawtooth reconnection occurred at 47.1s, this could imply that the q=1 surface is not present in the discharge thus no island is present at that surface. Nevertheless it is apparent that at 47.245s some reconnection takes place and temperature redistribution occurs. This is then followed by some form of magnetic turbulence before the energy quench finally occurs. Note the current redistributes itself at 47.255s ie the current distribution expands, the inductance decreases, the current rises and the plasma moves inwards shortly after the energy quench.

MHD ACTIVITY AND STRANGE ATTRACTORS[14]

The degrees of freedom or dimensionality (d) of a set of fluctuations can be obtained from the correlation integral [15]. This has been applied to a variety of the MHD activity on JET. For discharges in which no coherent mode activity is observed but only a low level of turbulent fluctuations ($\delta B/B \sim 10^{-6}$) the value of the dimensionality, d, is large. However for coherent mode activity with primarily m=2,n=1 then a value of the dimensionality of ~ 2.4-2.9 is obtained, depending on the case. The oscillating m=2,n=1 activity associated with the precursor to disruption shown in Fig.10, when restricted only to the n=1 perturbation gives an accurate value of d of 2.56. The convergence of the dimensionality to 2.56 is shown in Fig.15 where the log of the correlation integral as a function of the log of ρ is shown as the quantity k (the number of time displaced vectors used to evaluate the correlation integral) is varied from 1 to 16. This does indicate the presence of a strange attractor for this form of MHD activity. Three variables are involved, one being that which gives rise to the frequency of the mode and the rate at which it slows down due to whatever process and a coupling non-linearly to a higher n mode. There are also indications from non-linear calculations that the dimensionality should be approximately half the number of modes involved in the process. Thus we might conclude in this case that a total of 5 modes are involved. Certainly n=1, n=2, and probably n=3 are involved together with a range of m numbers from shaping and toroidal coupling. During the highly turbulent post disruption phase d ~ 4. Sawtooth activity has d = 1.

MHD ACTIVITY AND RF HEATING

The background activity level as shown in Fig.13 still remains at about 10^{-5} as measured at the wall on the outside of the plasma. However for central heating the ICRH sawtooth activity is substantially enhanced and for a discharge in which $q_\psi \sim 4.8$, I_p ~2MA, the sawtooth reconnection growing mode has a perturbation level at the wall (primarily m=2 n=1) of about 0.2%. In such a case the reconnection phase of the sawtooth is visible on the loop voltage as a negative spike (~-1V). Following the spike a slow mode (~ 250 Hz) is sometimes produced after some delay at a perturbation level of 3×10^{-4} with n=1 and m=4. If the heating zone is moved further out for the same value of q_ψ, then the sawtooth activity is diminished and the field perturbation level associated with the growing mode and reconnection falls by more than a factor of 10. The background perturbation level of 3×10^{-5} is unaffected. A number of shots with substantial RF heating show a significant precursor associated with the internal m=1. This oscillation may start some 50 ms before the reconnection phase. It grows and saturates at a perturbation level of ~ 5×10^{-5}. The poloidal mode number is 4 for q_ψ between 4 and 5. The mode is seen quite clearly on the ECE Fabry-Perot as shown in Fig.16. From the ECE the mode is believed to be m=1. The reconnection destroys the continuous m=1. The precursor is not always seen and sometimes a postcursor is detectable. In some cases there is no oscillating mode at all. All of these types of behaviour can be seen in a single discharge with the sawteeth alternating in their characteristics. These observations are similar to those on other additionally heated tokamaks where substanial precursor activity is observed before the reconnection together with a burst of activity associated with the reconnection and also the sawtooth reconnection is visible on the loop voltage.

CONCLUSIONS

At an S value of 10^8 the mode activity observed is similar to that on smaller tokamaks, however there is no evidence for mode activity when q_ψ passes through 3. Poloidal mode numbers between 2-6 and with toroidal mode numbers = 1 have been detected at amplitude levels, calculated at the resonant surface up to 3% at frequencies of between 0.5 and 1.5 kHz and with the vacuum vessel acting as a conducting wall. This activity is often accompanied by an n=2 mode typically at a level of $\sim$ 25% of the n=1. In some cases it can be triggered at a critical level of the n=1 perturbed field. During the initial current rise the activity is quite complex with m=2 and 3 soft disruptions, rapid current penetration being apparent. Occasionally the current rise may be free from activity. During the flat top phase of the discharge the fluctuation level falls to $\delta B/B_\theta$ at the wall $\lesssim 3 \times 10^{-5}$ though this level may rise when q_ψ falls below 4 for elliptical plasmas and 3 for circular plasmas. The sawtooth reconnection is directly visible as a rapidly growing mode with n=1 and its primary poloidal mode number at the edge may be 2, 3, 4 depending on discharge. Radio frequency heated discharges show little evidence for enhanced mode activity but the large sawteeth may lead to oscillatory mode behaviour detectable in the core of the plasma and on the coils at the wall, - it ceases at the sawtooth reconnection. Disruptions are characterised by growing primarily m=2, n=1 perturbations with $\tau_G \sim$ 10ms which lock when the perturbation level reaches $\sim$ 10G. The amplitude then increases approximately linearly to a level $\sim$ 3% which triggers the disruption or current termination. This may be accompanied in some cases by a fast 'm=2',n=1 mode whose growth time is < 100μs. At low q the mode growth is characterised by a more rapidly growing oscillatory phase and an exponential locked mode phase which occurs on a much shorter timescale. The observed poloidal variation in phase and amplitude of the MHD activity on JET with a single n is in qualitative agreement with theoretical predictions of tearing modes in non-circular toroidal geometry which require the existence of several poloidal harmonics and perturbed currents on several resonant surfaces, if present.

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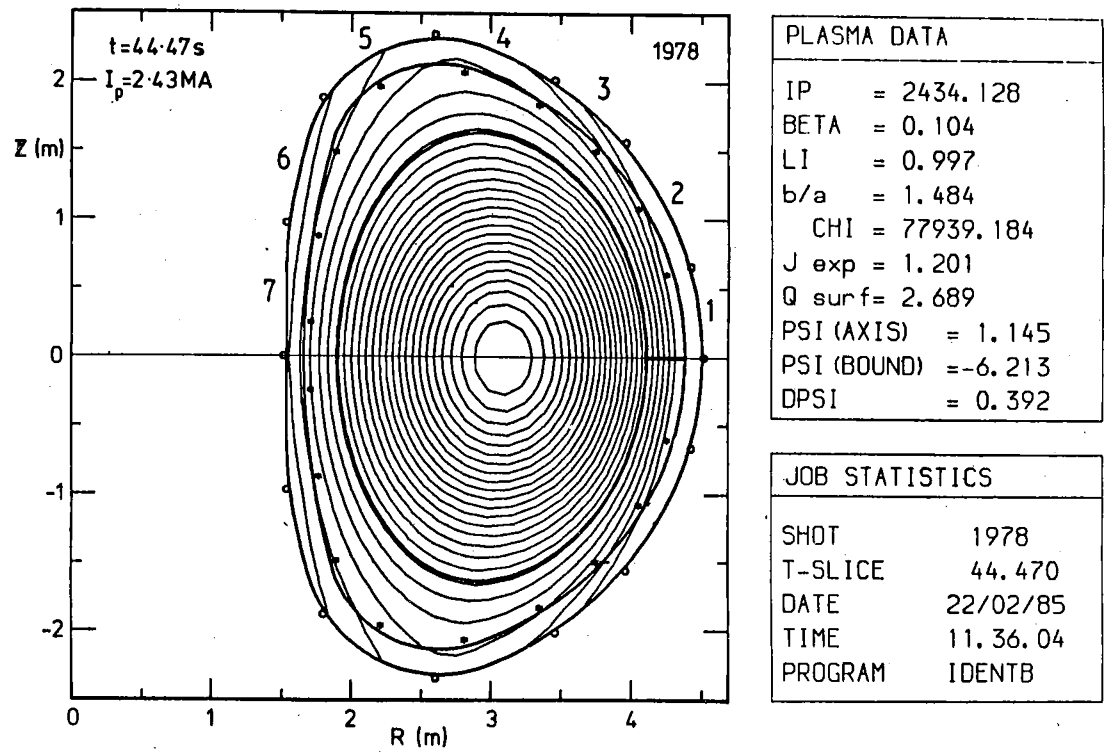

Fig. 1 Disposition of the 18 tangential field coils used in these investigations. Also shown and numbered from 1-7 are the 14 flux loops used to measure the radial component of the field. The figure also shows equilibrium flux contours at 44.47 seconds and the plasma current is 2.4MA.

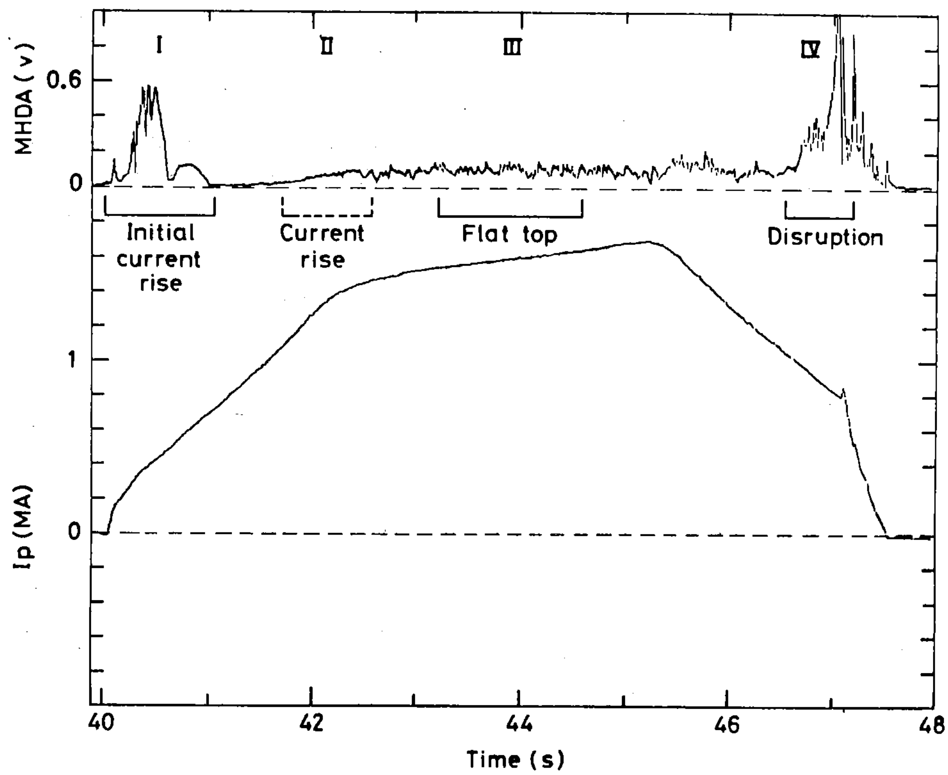

Fig. 2 MHD activity as a function of time on shot no. 1176. The MHD A signal shows an intense period activity during the initial current rise followed by a lower level during the slower current rise-II, a flat top period-III and the current run down phase often associated with disruption-IV.

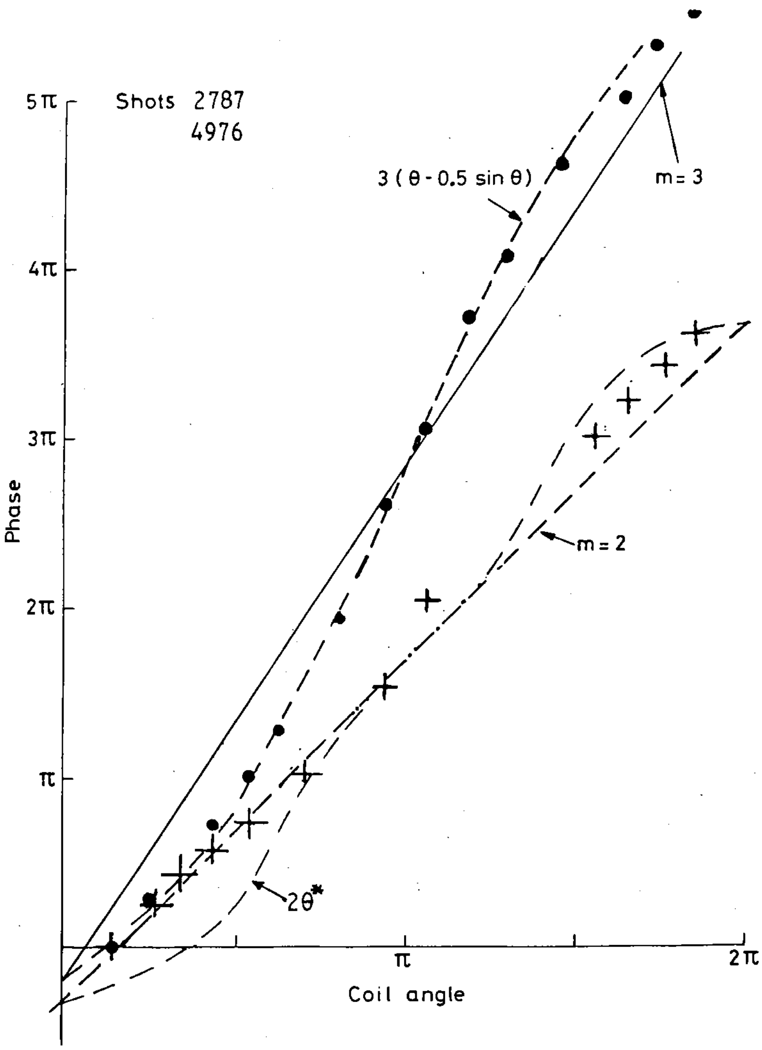

Fig. 3 Two examples of the measured phase as a function of the poloidal angle of the tangential coils for two different principle mode numbers $m=2$, $m=3$. For $m=3$ we show the predicted toroidal correction for circular magnetic surfaces. For $m=2$ the phase angle as a function of coil angle is shown for a D shaped plasma on JET with a single poloidal mode number $m=2$. This curve which is derived from the flux co-ordinate angle is labelled 2_θ*.

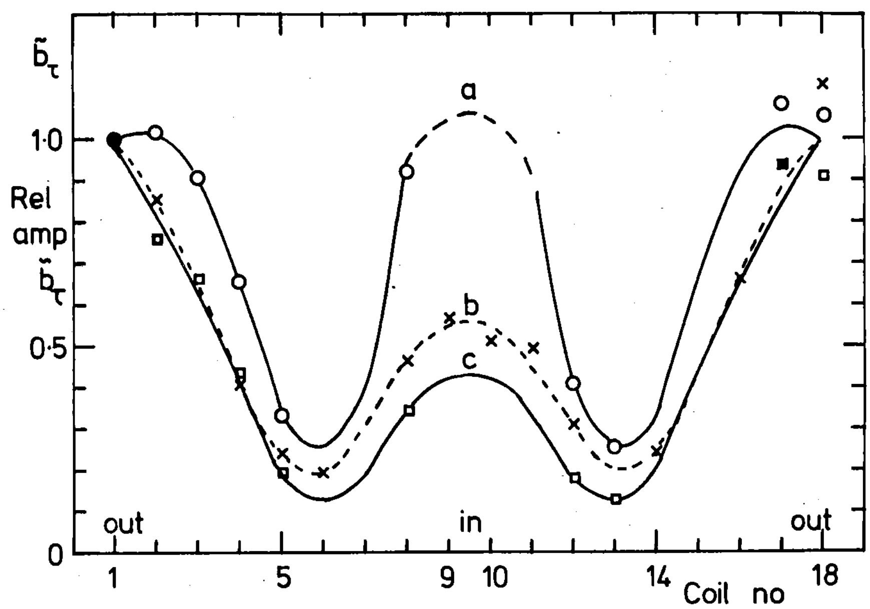

Fig. 4 Amplitude variation of the $m=2$ magnetic oscillations around the vessel for (a) $q_\psi \sim 2.7$. $b/a=1.5$ (b) $q_\psi \sim 4.5$, $b/a=1.2$ and (c) $q_\psi=6$, $b/a=1.5$.

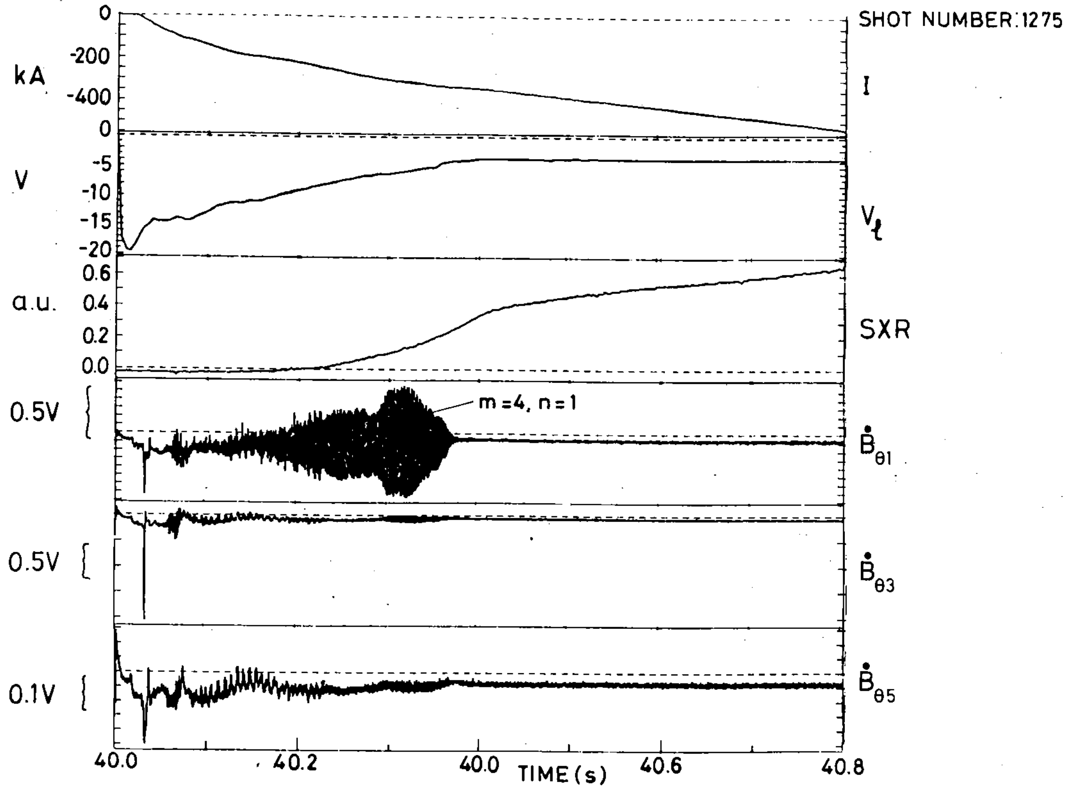

Fig. 5 Current, voltage, soft X-ray signal and tangential field coil signals during the initial current rise phase on shot no. 1275 when no disruptions are observed but only a single mode with $m=4$, $n=1$.

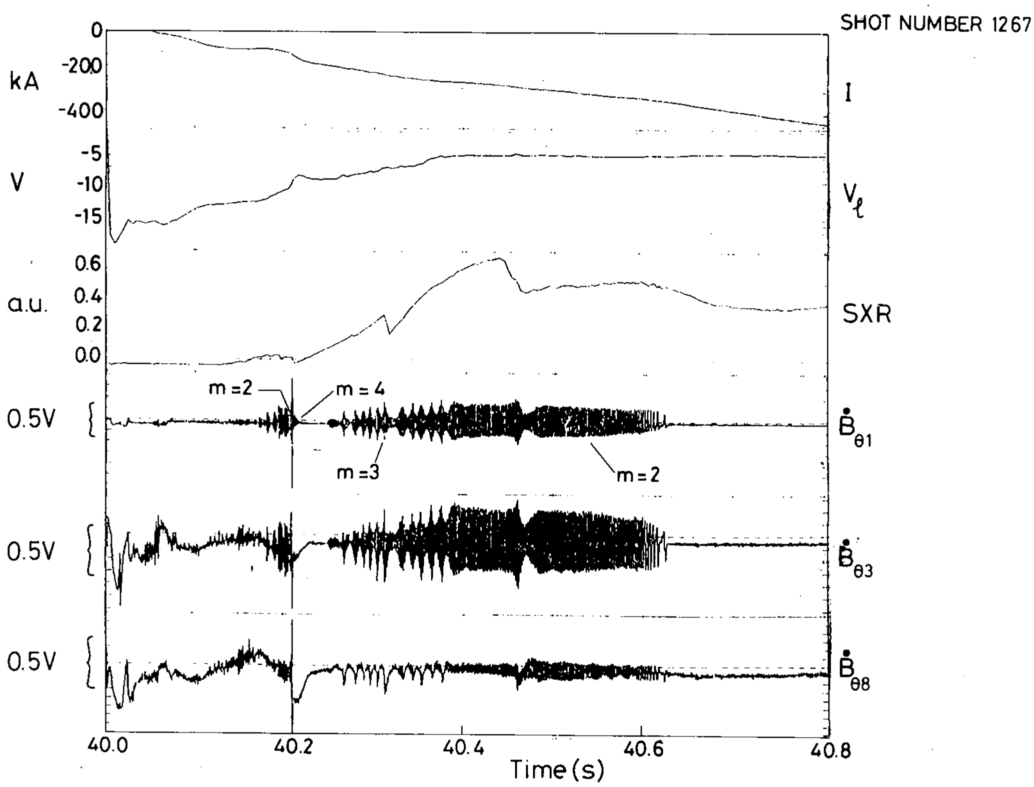

Fig. 6 Time evolution of current, voltage, soft X-ray signal and tangential field coil signals during the initial current rise phase on shot no. 1267. In this case a single large disruption is found at 40.21 s followed by $m=3$ and $m=2$ mode activity and finally by mode locking at 40.62 s.

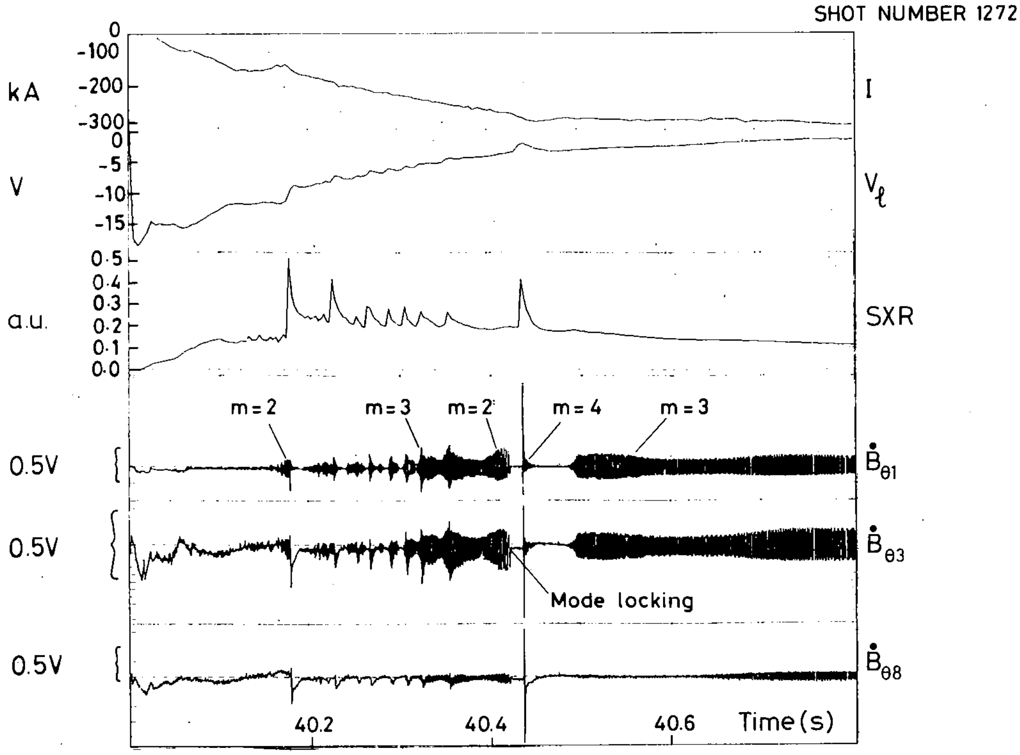

Fig. 7 Current, voltage, soft X-ray signal and tangential field coil signals as a function of time during the initial current rise on shot no. 1272. In this case the second disruption at 40.43 seconds is accompanied by locking of the $m=2$ mode. Following this disruption the mode activity is $m=3$ which changes to $m=2$ by 40.8 s.

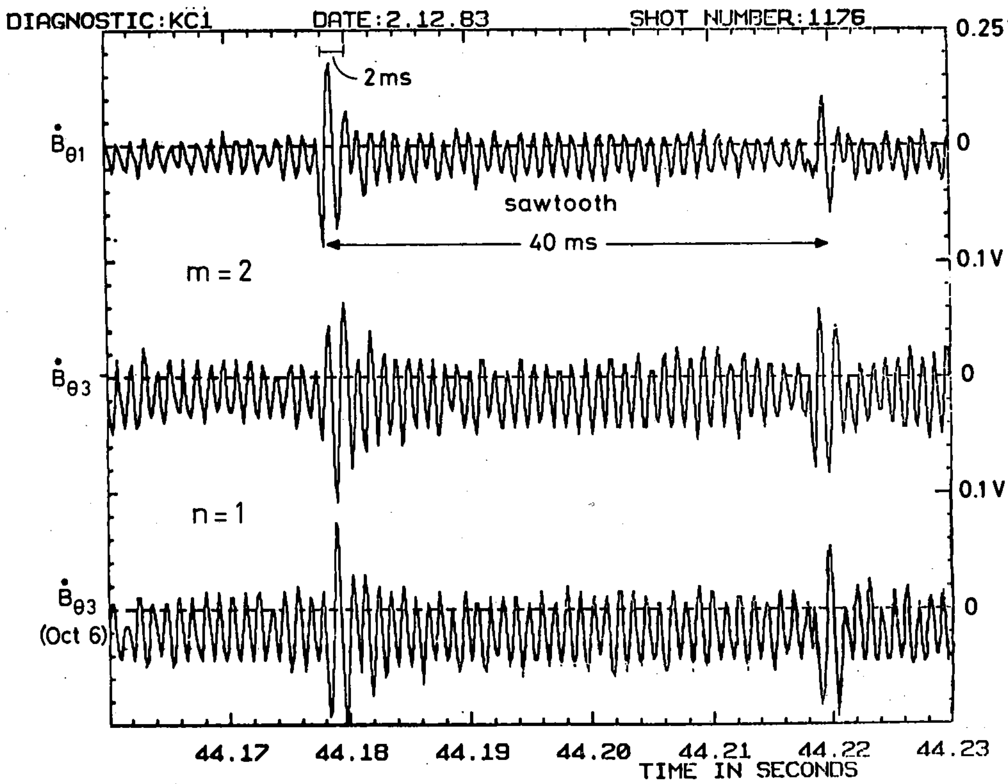

Fig. 8 Three tangential field coil signals during the currrent flat top phase for shot no. 1176 exhibiting the correlation of the $m=2$ $n=1$ activity with the sawtooth behaviour in the plasma. Current is 1.6MA and the sawtooth period 40ms. The poloidal field fluctuation amplitude reaches 0.03% at the reconnection phase of the sawtooth.

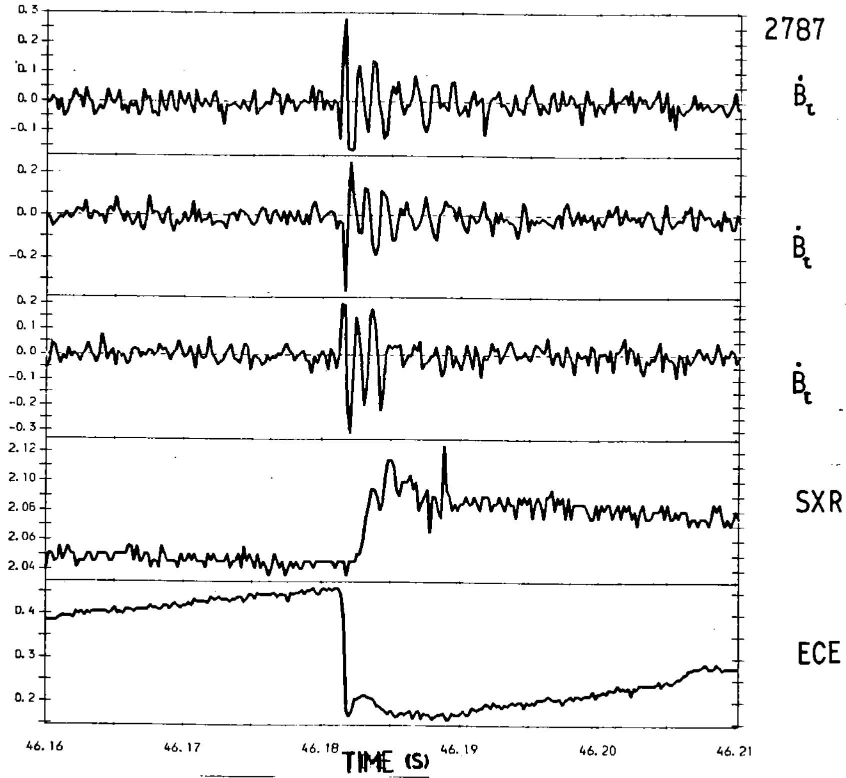

Fig.9 Three tangential field coil signals, a soft x-ray diode signal and ECE signal for shot no.2787 at the sawtooth reconnection. Primary mode observed on the coils in this case is $m=3$ $n=1$.

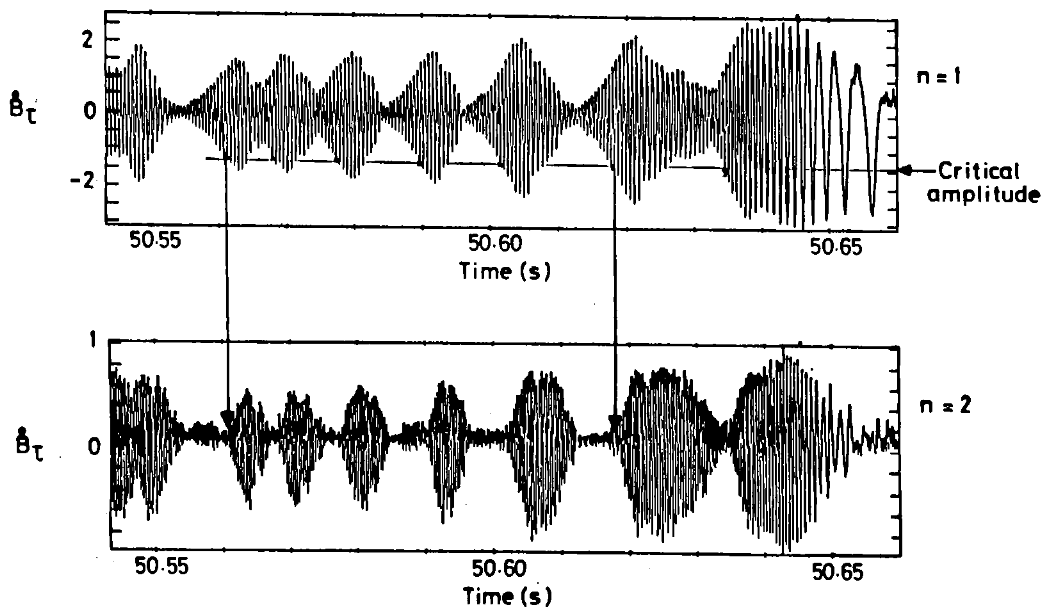

Fig.10 $n=1$ and $n=2$ mode activity showing the onset of n=2 activity at a critical $n=1$ level.

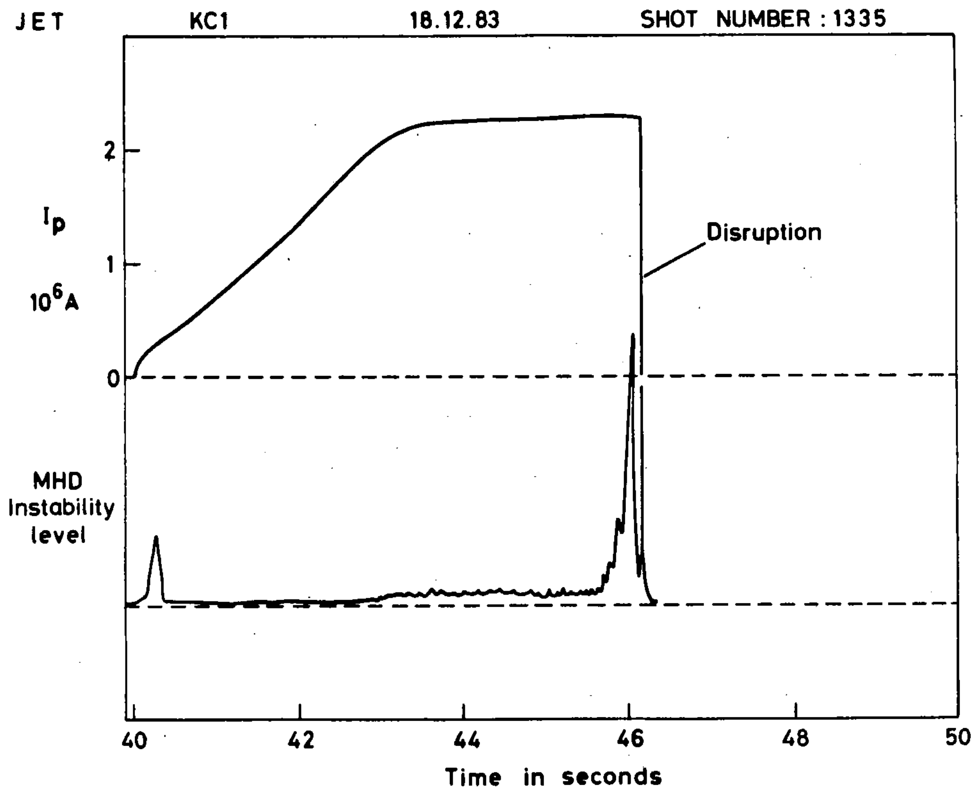

Fig. 11 Plasma current and the MHD A signal as a function of time for shot no. 1335 which leads to a strong disruption. The rate of current fall is about 10^8 A/s. The MHD signal level rises to >1% at the time of mode lock.

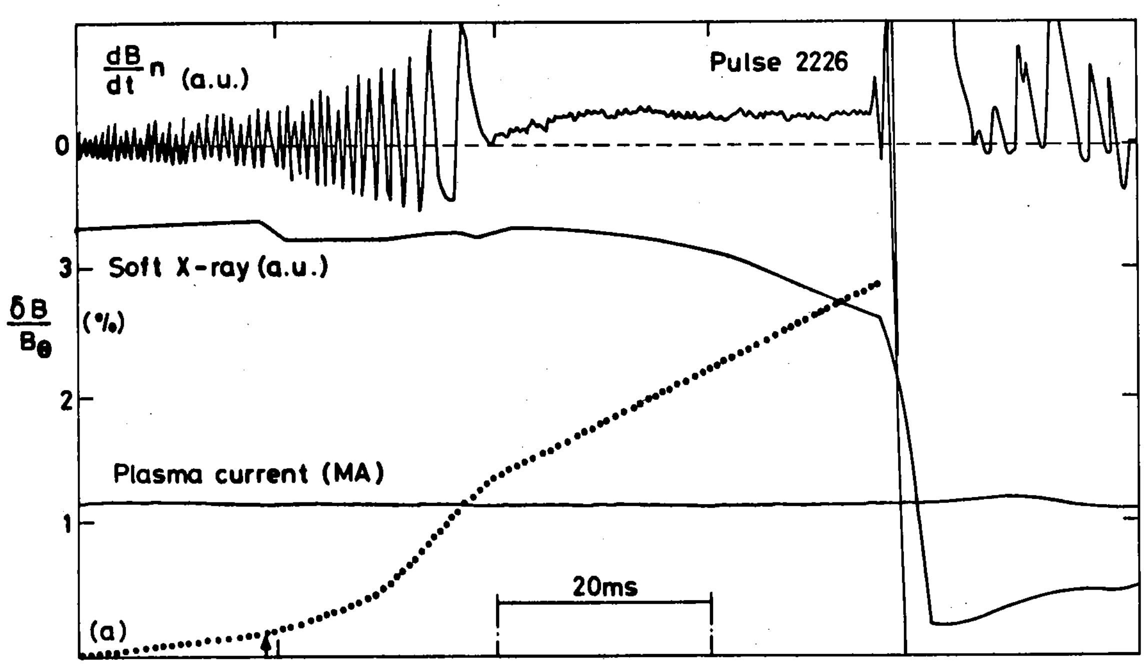

Fig. 12 A density limit disruption showing the precursor oscillating mode activity followed by mode lock which is then followed by a linear growth in the perturbed amplitude up to 3% when disruption occurs. Also shown is a soft x-ray signal. Note the fast mode behaviour at the time of disruption.

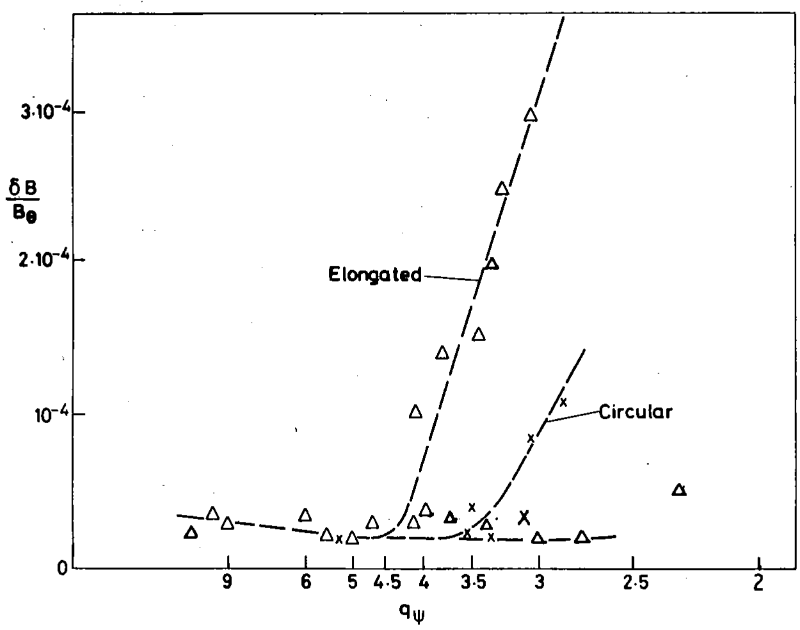

Fig. 13 The amplitude of mode activity normalised to the poloidal field at coil 1 as a function of q_ψ for elongated and circular plasmas. For $q_\psi < 4$ the amplitude can lie between the upper and lower curves.

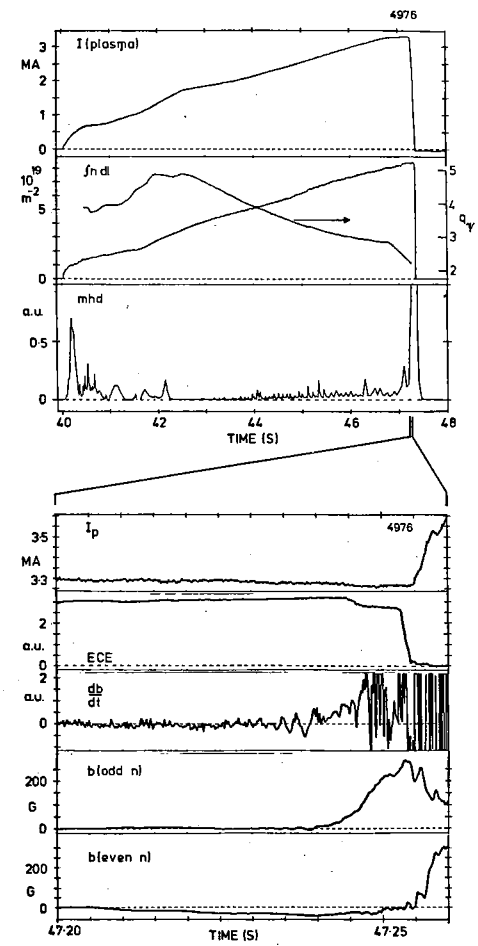

Fig. 14 Waveforms for a low q disruption with $q \sim 2.3$. The MHD signal is $m \sim 2$, $n = 1$ rectified and smoothed. The perturbed magnetic field signals are derived from coils of opposite octants. Note the drop in cyclotron emission when the mode amplitude becomes significant.

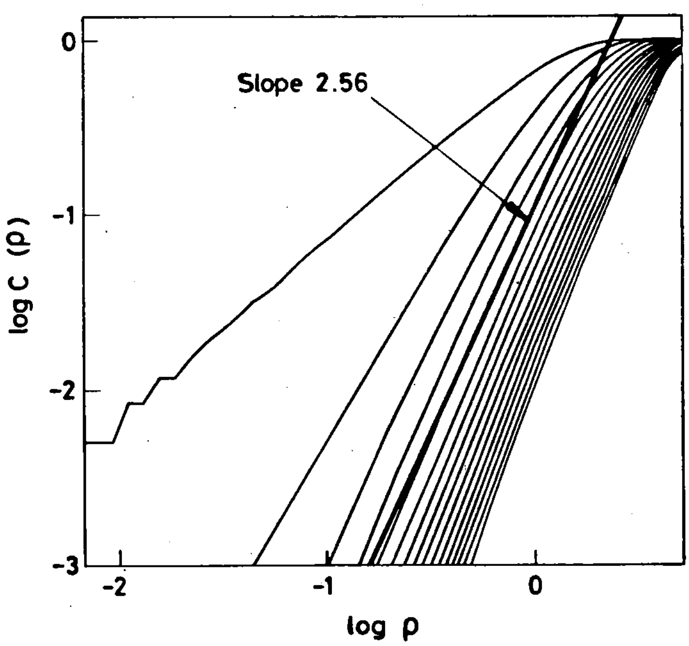

Fig. 15 Logarithm of the correlation integral as a function of log ρ for the MHD activity shown in Fig. 11 for $n = 1$. Different curves correspond to k varying from 1716.

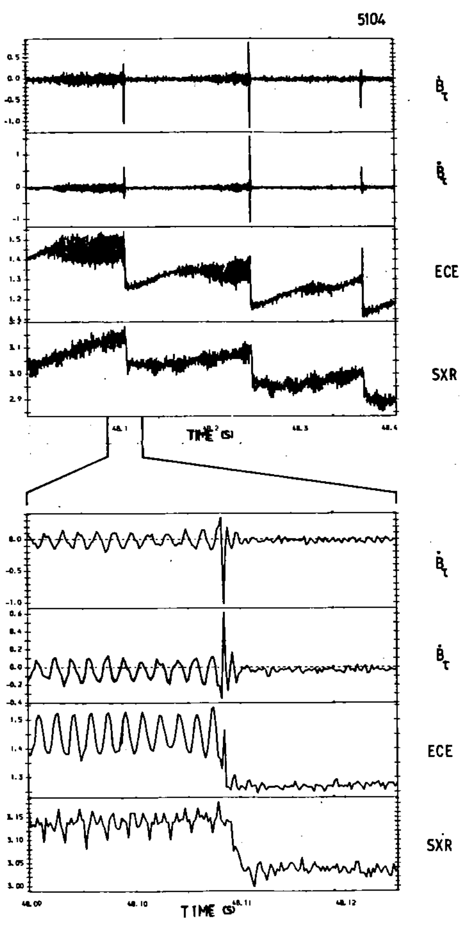

Fig. 16 MHD activity during radio frequency heating, the rate of change of tangential field coil signals, electron cyclotron emission signal and soft x-rays. The expanded traces show the internal precursor $m = 1$ activity which manifests itself as an edge magnetic perturbation with $m \sim 4$ $n = 1$ followed by rapidly growing $m = 1$, $n = 1$ instability which destroys the core of the plasma.