A STUDY OF DISRUPTIVE
INSTABILITIES IN THE PLT
TOKAMAK USING X-RAY TECHNIQUES

BY

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A Study of Disruptive Instabilities
in the PLT Tokamak
Using X-ray Techniques

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Disruptive instabilities in PLT have been analyzed using an array of surface barrier x-ray detectors viewing the plasma cross section along 20 chords. A wide variety of phenomena have been observed. A system of classification has been attempted, based upon: (1) the severity of the disruption, (2) the dominant precursor oscillations, and (3) the location of the onset of the disruption. Minor disruptions in which the disruption does not appear at the location of the island of the precursor oscillation have been observed, sometimes accompanied by seemingly independent higher frequency oscillations of different helicity localized near the point of the disruption. Major disruptions exhibit flatter central q-profiles, slowing of the oscillations, asymmetry with respect to the center of the discharge, and a correlation with high-Z impurity radiation.

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I. Introduction

The analysis of fluctuations in the intensity of continuum x-ray emission from discharges in tokamaks has become a standard technique [1-8]. The first measurements were made in relatively reproducible plasmas which exhibited cyclic "sawtooth-like" behavior of electron temperature and density, and related fluctuations of x-ray emissivity (which is largely due to recombination of partially ionized states of impurity atoms [9]). Extensive theoretical effort has been devoted to the interpretation of the accompanying $m=n=1$ oscillations (m and n refer to the poloidal and toroidal mode numbers of the wave); explanations have involved either magnetically or temperature-gradient driven modes [10-12]. A different type of discharge exhibited sinusoidal oscillations of $m=2$, $n=1$ symmetry; the steady-state mode structures have been measured and the related islands inferred in reproducible discharges. Theoretical studies of the observed $m=2$ tearing mode have been conducted [13-16]. More recently irreproducible phenomena such as disruptive instabilities have been investigated [2-4,7,8].

In this paper we describe the results of measurements of disruptive instabilities in the PLT tokamak. The experimental apparatus and technique are described in the next section and the results in the following section.

II. Experimental Procedure

The measurements described in this paper consist of integrals of the x-ray emissivity taken along chords of the plasma. Using an array of 20 surface barrier detectors (shown in Figure 1) viewing the plasma cross section at a given toroidal position through a thin beryllium window (in a fashion similar to that of a pin-hole camera) in the equatorial plane and other scannable detectors which view cross sections 80 and -30 degrees toroidally displaced with respect to the array, information on the radial profile of the equilibrium and the radial, poloidal, and toroidal structures of the perturbations can be obtained. Based on a set of assumptions, to be described, local structures can be derived in a manner similar to that used in tomographic reconstructions [2,6,17,18]. Results of such analyses are given for appropriate cases.

The detectors used in this study were most sensitive to radiation in the energy region from 1 keV to 13 keV and, together with the amplifiers, had a linear response at frequencies up to 1 megahertz and at detector currents less than 1 microampere (corresponding to a power of roughly 3.6 watts on the detector area of 2.5 cm x 0.2 cm). The signals were sampled by 20 A/D converters writing into local 4K buffers; the sampling rate was variable during a discharge and programmable up to 1 megahertz, thereby allowing a study of both the slow development of the discharge (with roughly 1 millisecond

resolution) and the fast transient behavior of instabilities (with typical wave frequencies of 2 kilohertz and minimum disruption time scales of tens of microseconds). After the discharge, the data were transferred from the transient analyzers into the PDP-10 for display and analysis.

The analysis of periodic data has been described previously [6], the inversion of the line integrals being given in reference [19]. Basically, there are several analyzable models for periodic signals which can lead to the inversion of the line-integral data into local emissivities. (1) If the plasma is a rigid rotator, the poloidal harmonics generate frequency components which are due to the Doppler shift and are proportional to the mode number in the direction of rotation. With few exceptions this model permits the complete reconstruction of the plasma cross section with a view from only one angle (similar to rotating the patient before a tomographic scanner). (2) Nonuniform rotation demands more views of the plasma; since the amplitudes and phases of the poloidal and toroidal harmonics are not available from a temporal decomposition, they must be determined from an actual Fourier analysis of the mode structure viewed from as many angles as necessary to avoid aliasing. Such a large number of windows is not generally available on tokamaks and thus the standard assumptions are that a small number of modes of small m and n are present; analysis of modes with large m and n are difficult to analyze by means of chordal observations in a cross section

due to the phase-averaging along the line of sight; views more parallel to the magnetic field are more suitable for modes with large m and n , but finite ratio m/n .

In cases where the signals are not periodic and numerous angular views are not available, the inversion of the line-integral data is not unique and can be performed only in conjunction with rather arbitrary sets of assumptions. However, inspection of the raw data is remarkably illustrative in these cases despite the ambiguities.

III. Results

The discharges described in this report were typical for PLT with plasma currents near 500 kA and toroidal magnetic field 35 kilogauss which, together with the dimensions of PLT (major radius 130 cm, minor radius 40 cm), give $q(a) = 4.3$.

Based on observations of several hundred disruptions, three general statements can be made:

(1) Disruptions are of various intensities, ranging from those that are barely visible on traces of x-ray emission to those that result in catastrophic interruptions of the plasma current, density, and other macroscopic quantities. This diversity has prompted a classification of the disruptions according to their severity -- calling "minor" the ones which are visible on the x-rays but do not seriously disturb other parameters and "major" those that bring the discharge to an abrupt termination.

(2) Disruptions can be preceded by several different MHD phenomena, including dominant precursors of $m=1$, 2, or 3 symmetry and subdominant faster oscillations. In other cases, no fluctuations were observed before the disruption, due either to an absence of asymmetries or to a lack of rotation of the modes. These observations suggest a categorization of the disruptions according to the observed MHD precursors.

(3) A third classification can be based on the location of the node of the disruption. Generally, during the disruption, inside some position in the discharge the x-ray emissivity decreases

and the related energy is transported outward to a position where the x-ray emissivity rises. The location of the intermediate point where the average emissivity is undisturbed is the third element of our classification scheme. In cases where a mode with an appropriate ratio m/n is present, the location of discrete values of q ($= m/n$) can be determined and used to label the position of the disruption with an approximate value of q .

Based on these characterizations we will separately describe major and minor disruptions.

III. A. Minor Disruptions

Table 1 is a grid containing information on minor disruptions observed on PLT. The m-axis displays the dominant precursor oscillation and the q-axis the location of the disruption in the q-profile, which was determined by observations of the radial mode structures of the precursors.

The first block ($m=q=1$) refers to "internal disruptions" or "sawteeth" and other activity related to current buildup, about which we will not discuss further.

The $m=q=2$ block refers to the standard disruption which was studied on the ST Tokamak, in which the disruption proceeded from near the $q=2$ island.

The two other blocks in the $m=2$ column refer to the common cases where the node of the disruption was located well within the $q=2$ radius, at a position of lower q . In one case, faster $m=n=1$ oscillations were observed near the node, prompting a classification as $q=1$.

In the $m=3$ column are listed disruptions which had precursors of $m=3$ symmetry, which occurred mostly in discharges with hollow temperature profiles and no $q=2$ point (or a marginal $q=2$ point).

In the last column are indicated disruptions which were preceded by no visible oscillations and therefore no information on the q-profile was available from mode structures.

The next sections will deal with examples of data from these categories.

III. A. 1. $m=2$ $q=2$ Minor Disruptions

The $m=q=2$ disruption is the "classical case" discussed previously [2]. In the ST tokamak, the evolution of the island near $q=2$ was analyzed and the structure was found to expand both inward and outward, effecting a collapse of the plasma column; the $m=2$, $n=1$ precursors were shown to be consistent with assumed radial mode structures for tearing instabilities.

In this section we (1) display the raw data taken along various chords of the plasma, (2) invert the line-integral data to determine local quantities, and (3) describe the disruption.

Figure 2 is a plot of the x-ray intensity integrated along the diameter of the plasma cross section as a function of time (in milliseconds) since the beginning of the discharge. The temperature rose over a period of roughly 150 milliseconds, after which time a series of disruptions ensued. Since the macroscopic parameters were only slightly affected and the x-ray intensity did not drop by a large factor, the disruptions are labeled "minor".

Figure 3 shows an expanded view of traces in the same discharge including a minor disruption. The horizontal scale is time into the discharge in milliseconds. The vertical label refers to the tangent minor radius of the chord in centimeters ($0 < r < 30$ cm). For visibility, the signals at radius r have been normalized to the same size and displayed between r and $r + 2$ cm

on the radial position scale; the bars on the right hand side of the figure refer to the normalization and offsets used in the display, the length of the bar in the left column being proportional to the maximum of the signal minus the minimum (i.e., the factor by which the trace must be multiplied to return to the same scale), in the right column being proportional to the average value (the offset), and in the middle column to the ratio of the values in the outer two columns. The limiter was located at 40 cm. The minor disruption occurred near 177.8 milliseconds. There were two locations of nodes with phase reversal in the radial mode structure prior to the disruption; the outermost, near 15 cm, is related to the $q=2$ pole in the mode structure; the inner reversal, near 8 cm, is due to cancellation in the line integral over the poloidal structure. Flattening of the lower portion of the 16 cm trace is interpreted as island structure; the small peaks, sometime larger, are possibly due to an $m=4$ component related to a temperature maximum inside the island.

The location of the disruption can be defined as that radius inside of which the emissivity initially drops and outside of which the emissivity rises. In this disruption, the 14 cm trace retained its average value and can be identified as the location of disruption, subject to refinement by Abel inversion of the equilibrium before and after the disruption. Since the disruption occurred adjacent to the radius where $q=2$, this minor disruption can be characterized as $m=q=2$.

Another feature of this disruption, which is present in many cases, is the existence of faster oscillations at the onset. At this time, insufficient data has been acquired to determine the generality or relevance of the high frequency oscillations.

In order to analyze the mode structure in the case of single-modes, one can model the process as the rotation of a structure having poloidal and toroidal components of symmetries $m=n=0$ and the measured m and n of the mode (based on phase comparisons at different angles). By treating the temporal average as the equilibrium $m=n=0$ component and the fluctuating signal as the perturbation with the poloidal and toroidal structure, the problem can be separated into two parts relating to the inversions of the radial profiles of the line-integrated equilibrium and perturbations.

Figure 4 shows plots of the amplitude and phase of the raw line-integrated fluctuation signals; the open circles in the phase display refer to the raw phase information. Since the various views pass through a single window in the equator of PLT and thus are tangent at slightly different poloidal angles, the raw phases have to be corrected for the poloidal displacement; the linearly-connected closed circles show the modified phases, which were also translated to zero phase shift along the central chord. The two locations of phase reversal are apparent at 8 and 15 cm. A feature which persists throughout the analysis is the radial phase shift outside the radius of $q=2$.

This is in apparent contrast with theoretical predictions which, for an almost cylindrical machine like PLT, indicate that the signals should be nearly either in phase or out of phase by 180 degrees at different radii at the same poloidal position.

As described in Reference [6], the corrected signals in phase and 90 degrees out of phase with the central integral can be analyzed independently. Figure 5 shows both the line integrated and inverted profiles for the two sinusoidal components. The solid line refers to the component in phase with the central line integral fluctuation and the dotted line to the orthogonal component. The exact inversion of the $m=2$ line integral can lead to non-zero fluctuating emissivity at the center; however, since the central fluctuation must be unique and since it has a poloidal variation, it must vanish at the center. This physical argument imposes a constraint on the data such that the inversion must give a vanishing result at the center; the extent of the modification of the raw data necessary to satisfy this constraint is a measure of the error, which is indicated by the dashed line.

Having obtained the radial profile of the $m=2$ component of the x-ray emissivity and the $m=0$ equilibrium, the total structure can be reconstructed, as shown in Figure 6. The solid line refers to the unperturbed equilibrium and the dotted lines to the total profile at positions separated by 90 degrees.

The radius of the $q=2$ surface was moved outward to 18 cm from the position of the node in the line integral at 15 cm, as expected since the presence of a node requires the cancellation of the positive outer contribution by the negative contribution inside the $q=2$ radius.

Another representation of the same inverted data, a contour plot, is shown in Figure 7. The flat region and phase reversal near 18 cm radius are apparent; the closed "island" structures are due to the peaks at 7 cm and 18 cm shown in Figure 7; the general picture is in rough accord with predictions of tearing mode theory, although the resolution near the island is insufficient to faithfully reproduce the source image.

Similar analysis of the line-integral traces immediately after the disruption, shown in Figure 8, indicates that the effect of the disruption was a modification of the profile similar to that expected from island formation, with the decrease of the emissivity at inner radii, as shown in Figure 9 where the equilibrium profiles before and after the disruption have been superimposed.

III. A. 2. $m=2$ $q < 2$ Minor Disruptions

Many minor disruptions with dominantly $m=2$ $n=1$ precursor oscillations in which the disruption occurred at radii well inside the location of the $q=2$ point (determined from the $m=2$ mode structure) have been observed on PLT. The blocks $m=2$ $q=1$ and $m=2$ $q=1.5$ on Table 1 refer to these cases.

Figure 10 shows the temporal behavior of the line-integrated intensity on various chords for such a disruption. From the dominant 2 kHz $m=2$ oscillation the $q=2$ point can be located at 20 cm. The breakpoint in the disruption occurs at 12 cm, at which point are observed faster (8 kHz) oscillations during the last half-period of the $m=2$. Analysis with other detectors poloidally and toroidally displaced indicates that this faster mode is described by $m=n=1$. Detailed inspection of the traces around 191 milliseconds indicates that the faster oscillations inside 10 cm are 180 degrees out of phase relative to those outside 10 cm; this suggests the location of $q=1$. Similarly, those traces inside 10 cm exhibit a sudden decrease and those outside 10 cm a sudden increase after the disruption at 191.2 milliseconds. The correspondence of the location of the node of the oscillation and the location of the disruption prompts an identification as an $m=2$ $q=1$ disruption, involving seemingly independent modes of mixed helicities.

Figures 11a, b, and c show the faster oscillation and the disruption at $r=0$ cm, ± 4 cm, and ± 8 cm. The poloidal positions of the two 4 and the two 8 cm detectors differ by 172 and 165 degrees respectively, accounting for the phase shifts of the $m=1$ oscillations.

The frequency difference (of a factor near 4) between the $m=1$ and $m=2$ modes opposes the concepts of either a rigid rotation (which would give a factor of 1/2 since the doppler shift would be proportional to the mode number in the direction of motion) or as a linear toroidal eigenmode (which would give a factor of unity since the toroidal perturbation of the Hamiltonian is at rest relative to the laboratory frame so that the various cylindrical poloidal components of the true toroidal eigenmode would have the same frequency in that frame). Hence, the models for coherent mode coupling seem inapplicable for the description of this disruption.

Figure 12 illustrates another case where the mini-disruption (at 250 milliseconds) occurred near 12 cm while the phase reversal related to $q=2$ occurred near 18 cm; in the second disruption (at 254 milliseconds) the position of the $q=2$ point seems unchanged (or even shifted inwards) while the disruption location moved to near 14 cm. Hence, the q -profile inside $q=2$ appears to have steepened. Also visible on the 16 cm trace is a pattern interpreted as due to island formation at $q=2$; prior to the first disruption a slight flattening of the trace is seen, presumably related to the flat profile of x-ray emissivity within an island.

In the case of the second disruption, the precursor trace at 16 cm exhibited a double-frequency component which could be interpreted as the result of a relative maximum of the x-ray emissivity within the $m=2$ islands; such a peaking of the emissivity would be due to maximum electron temperature, density, or radiation enhancement due to the presence of impurities.

Another feature of this disruption is the presence of much higher frequency fluctuations at the time of disruptions. While such subdominant precursors are a common occurrence, they are not always present and may be unrelated to the disruption.

III. A. 3. $m=3$ Minor Disruptions

Under some circumstances the electron temperature and x-ray emissivity profiles in PLT possess a relative minimum at the center of the discharge. In some of these cases, particularly those wherein the q -profile inferred from neoclassical conductivity and uniform impurity concentration exhibits no $q=2$ points, $m=3$ $n=1$ modes were observed. Figure 13 shows such a case which resulted in minor disruptions, a small one at 340 milliseconds and a stronger one at 342 milliseconds. In this case, based upon these assumptions, the value of q at the limiter was 4.4, at the center 3.8, and at the minimum at 16 cm near 2. The predicted radii where $q=3$ were 6 cm and 30 cm.

Since an $m=3$ mode is of odd symmetry, the line integral through the center vanishes, as seen in the figure. As with the $m=2$ mode, a node due to integration through the poloidal structure is expected at a radius intermediate between the center and the point where $q=3$. However, the Abel inversion, which removes this node, is difficult for hollow profiles since relatively large contributions from outer radii are subtracted from the total signal to derive a small result; for this reason the inversion is reliable only at radii outside the maximum of the emissivity. Another source of phase reversal in the local emissivity is the hollow equilibrium profile since the fluctuation is due to a convection of the fluid; since the displacement changes sign at the resonant points,

phase reversals occur at the resonant surfaces and at the emissivity maxima. For these reasons, the successful inversion of an $m=3$ mode in a hollow emissivity profile has not been achieved at this time.

Theoretical analyses of tearing mode stability for cases with two singular points have been performed for the experimentally measured profiles of temperature and density [20]. To avoid the difficulty of solving the radial differential equation with two singular points, the approximation which was used for the mode peaked at one singular point involved an artificial node at the distant singular point and the calculation of δ -prime and δ -critical [14] at the adjacent singular point. For this particular case the mode peaked at 7 cm was unstable (δ prime = 9.05, δ critical = -29.83) and the mode peaked at 30 cm was stable (δ prime = -1.52, δ critical = 1.37). In other cases, the opposite arrangement was true, with the outer mode unstable.

The node of the disruption occurred near 22 cm, which is distant from the $m=3$ islands and corresponds to a value of q well below 3. Figure 14 shows Abel-inverted equilibrium emissivity profiles before (hollow) and after (peaked) the disruption. Energy appears to have been transported to both the center and the edge.

Faster oscillations (near 11 kHz) were observed at times during the 10 milliseconds preceding the minor disruption. The radial wavelength of the line integral was short (roughly 5 cm)

which would require a high m to be explicable by radial integration effects, since in addition to the local nodes of the mode structure, $m/2$ or $(m-1)/2$ nodes are introduced by integration over the poloidal structure for even or odd modes respectively. Insufficient data has been obtained to comment on the relevance of the higher frequency oscillations.

III. A. 4. Minor Disruptions With No Visible Precursors

In some cases, minor disruptions can occur with no apparent precursor oscillations for several tens of milliseconds prior to the disruption. Figure 15 illustrates such a case in which a minor disruption occurred near 16 cm but no oscillations were observed for 15 milliseconds. The lack of observed fluctuations may be due to an absence of either asymmetries or rotation.

III. B. Major Disruptions

As described elsewhere [2], at low values of q at the limiter or at high densities, catastrophic interruptions of plasma current, density, and electron temperature can occur. These disruption are terms "major".

On PLT, only two major disruptions have been properly documented with x-ray methods throughout the sequence and Thomson scattering immediately preceding the disruption. In these two cases there were three similarities: (1) the $q=2$ surface was at a radius larger than normal (i.e., 28 cm compared to 20 cm); (2) during the disruptions a vertical asymmetry existed, similar to that reported in reference [4]; and (3) heavy impurity radiation near 50 Angstroms rose in magnitude rapidly (in a time or order 100 microseconds) with the major disruption, in contrast to the situation in minor disruptions where the impurity radiation followed the pattern of the soft x-ray emission; the impurity radiation rose to such a magnitude that the power loss was greater than the input power, contributing to the termination of the discharge.

Figure 16 shows the central x-ray trace from a major disruption in a high-density helium discharge; at 600 milliseconds the average electron density was 10^{14} cm^{-3} , the peak electron temperature 850 electron volts, and the plasma current 510 kiloamperes. At 599 milliseconds the final sawtooth (cf. Figure 19) indicated the location of the $q=1$ surface at roughly 10 cm, in agreement with Thomson scattering measurements (shown in Figure 17),

which in addition gave the $q=2$ point at 28 cm. The major disruption lowered the average emissivity by 80 percent.

Figure 18 shows the traces along vertically displaced chords. Growing oscillations with decreasing frequency are seen prior to the disruption; the following two figures show blowups of (1) the oscillations and (2) the disruption itself. In Figure 19, the final sawtooth is seen at 599 msec and the later oscillations are seen to grow in a time of order 3 wave-periods. The radial mode structure is unusual in that there is no clear geometric node of the oscillations at intermediate radius (due to the integration over the poloidal structure), which would be expected for an $m=2$ mode as described earlier; instead, the relative phases of the oscillations vary with time since the modes at intermediate radii seem to have frequencies slightly different from those at other radii. The oscillations at ± 12 cm are out of phase by nearly 180 degrees, whereas those at ± 8 are somewhat mixed, probably due to a superposition of $m=1$ and $m=2$ modes; the appearance of the odd mode between 6 cm and 14 cm is likely the result of the expected geometric node of the $m=2$ radial line integral. The oscillations at radii greater than 14 cm (after correction for slight poloidal displacements) are roughly 180 degrees out of phase with those at radii less than 6 cm, as expected for the $m=2$ line integral; the fundamental component of the trace at the center is pure $m=2$ since the $m=1$ vanishes upon integration along the line of sight. One possible model for the apparent slight discrepancy in the frequencies of the oscillations is

the relative growth of one of the poloidal components of equal frequency. Such behavior, involving coupled modes, is not unusual although it is not observed in all cases. In other major disruptions only an $m=2$ component is apparent, suggesting that modes of mixed helicities may not be an essential component of disruptions.

Figure 20 shows the disruption itself, seeming to propagate from the outside, near the $q=2$ surface, to the inside in roughly 500 microseconds. The decrease is not symmetric, however, appearing to drop at different rates on opposite sides of the discharge. Figures 21a through 21e show the traces of the disruption at the center and at oppositely positioned detectors at 2, 4, 8, and 12 centimeters from the center of the discharge. The line-integrated emissivities at 0, 2, and 4 centimeters rise slightly prior to the disruption (at 608.6 milliseconds) while one of the traces rises and the other drops at 8 and 12 cm. The later asymmetry of the decrease, from 609 to 610 milliseconds, is largest at greater radii, where a single temporal oscillation is also present.

The last disruption to be discussed is shown in Figures 22 and 23. As seen in the first figure, the discharge suffered slight disruptions during the startup phase at 60, 80 and 110 milliseconds, another disruption prior to the steady state phase at 180 milliseconds, exhibited sawteeth from approximately 200 milliseconds until 340 milliseconds and terminated with a series of disruptions. During the steady state phase the average density was $3 \times 10^{13} \text{ cm}^{-3}$ and the peak electron temperature 2 kiloelectronvolts.

Figure 23 shows the signals from 17 detectors located on both sides of the center of this discharge. Within 150 microseconds, a wavefront appears to have propagated from one side (near the $q=2$ surface) through the center to the opposite side of the discharge. Since on this time scale (which is an order of magnitude slower than typical ion acoustic scales) no significant emissivity gradients can have been supported within a surface, this apparent vertical motion indicates some exceptional displacements and deformations of the surfaces, involving coupled even and odd modes of comparable magnitude; since the traces appear to have remained relatively constant before the sudden decrease rather than rising when other traces dropped, some loss mechanism other than simple translation seems to have been present. One possibility for this loss is radiation in the energy region near 50 Angstroms, which rose suddenly (i.e., in 100 microseconds) by over an order of magnitude to a level greater than that of the input power, seemingly terminating the discharge. Insufficient data is available to conclude whether the asymmetry and enhanced radiation losses are essential components of major disruptions.

IV. Conclusions

Our investigations have dealt with several members of a wide variety of disruptions. Minor disruptions, in which the macroscopic observables such as current and average density are relatively unaffected, can be accompanied by dominant precursor oscillations of $m=1$, 2, or 3 symmetry along with subdominant oscillations usually of a higher frequency; in other cases, the minor disruptions may be unaccompanied by oscillations, presumably due to an absence of either asymmetries or rotation. The location of the minor disruption may occur at a position intermediate between that of the dominant precursor island and the center of the discharge.

For major disruptions, although the quantity of data is insufficient to permit statements concerning the generality of the observations, a disruption with vertical asymmetry has been monitored in a discharge with a somewhat flat inner q -profile including $q=1$ and 2 points, with coupling between even and odd modes appearing to be essential for explaining the propagation pattern; high- Z impurity radiation has been seen to increase in magnitude simultaneous with the disruption. A possible model for disruption in such an equilibrium is described in Reference [2].

Lastly, two dimensional image reconstruction techniques have been applied in the case of $m=2$ oscillations to recover local mode structure from line-integral measurements.

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References

- [1] VON GOELER, S., STODIEK, W., SAUTHOFF, N., "Studies of Internal Disruptions and $m=1$ Oscillations in Tokamak Discharges with Soft X-ray Techniques", Phys. Rev. Lett. 33, 1201 (1974)..
- [2] VON GOELER, S., "X-ray Measurements on the ST Tokamak", (Proc. 7th European Conference on Plasma Physics and Controlled Nuclear Fusion, Lausanne, 1975).
- [3] KARGER, F., et al., "On the Origin of the Disruptive Instability in the PULSATOR I Tokamak", (Proc. 6th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Federal Republic of Germany, 6-13 October, 1976).
- [4] MIRNOV, S.V., SEMENOV, I.B., "Observation of the Fine Structure of a Disruptive Instability in a Tokamak", (Proc. 6th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Federal Republic of Germany, 6-13 October, 1976).
- [5] CALLEN, J.D., JAHNS, G.L. "Experimental Measurement of Electron Heat Diffusivity in a Tokamak", Phys. Rev. Lett. 38, 491 (1977).
- [6] SAUTHOFF, N.R., "Analysis of Magnetohydrodynamic Modes in Tokamaks", (Proc. of the SPIE 106, 40, 1977).
- [7] TFR GROUP, "The Disruptive Instability in the TFR Tokamak", (Proc. 3rd International Congress on Waves and Instabilities in Plasmas, Palaiseau, France, 1977).
- [8] SAUTHOFF, N.R., VON GOELER, S., STODIEK, W., "X-ray Fluctuation Measurements on the PLT Tokamak", (Proc. 3rd International Congress on Waves and Instabilities in Plasmas, Palaiseau, France, 1977).
- [9] VON GOELER, S. et al., "Thermal X-ray Spectra and Impurities in the ST Tokamak", Nuc. Fus 15, 301 (1975).

- [10] WADDELL, B.V., ROSENBLUTH, M.N., MONTICELLO, D.A., WHITE, R.B., "Non-linear Growth of the $m=1$ Tearing Mode", Nuc. Fus. 16, 528 (1976).
- [11] ROGISTER, A., HASSELBERG, G., "Interpretation of Precursors of Internal Disruptions", Phys. Rev. Lett. 37, 906 (1976).
- [12] DRAKE, J.F., et al., "Kinetic Theory of the Internal $m=1$ Resistive Mode" (to be published).
- [13] FURTH, H.P., et al., Phys. Fluids 16, 1054 (1973).
- [14] GLASSER, A.H., et al., Phys. Fluids 19, 567 (1976).
- [15] WHITE, R.B., et al., "Saturation of the Tearing Mode", Phys. Fluids 20, 800 (1977).
- [16] WHITE, R.B., et al., "Nonlinear Tearing Modes in Tokamaks", Princeton Plasma Physics Laboratory Report PPPL-1282 (1976).
- [18] Special Issue on Computed Tomography, Optical Engineering 16 (1977).
- [19] SAUTHOFF, N.R., VON GOELER, S. (to be published).
- [20] GLASSER, A.H., private communication.
- [21] WHITE, R.B., MONTICELLO, D.A., ROSENBLUTH, M.N., "Simulation of a Major Tokamak Disruption", Princeton University Plasma Physics Laboratory Report PPPL-1364 (1977).

PLT DISRUPTION CLASSIFICATION

MINOR

DOMINANT PRECURSOR OSCILLATION

		m = 1	m = 2	m = 3	None
S T A R T I N G L O C A T I O N	q = 1	"Internal Disruptions" "Sawteeth"	Fast m = 1 Precursors		
	q = 1.5		?		No
	q = 2		"Classical ST Disruption"	?	q
	q = 2.5			"m = 3 Disruption"	Information
	q = 3

766238
Fig. 1. Array of surface barrier detectors used for imaging
the plasma through a slot aperture.

776140
 Fig. 2. Central line-integrated x-ray emissivity for a discharge with $m=2$ $q=2$ disruptions.

X-RAY INTENSITY (RADIUS, t)

776132
 Fig. 3. Line-integrated emissivity at 15 radial positions showing the $m = 2$ precursor oscillations and the $q = 2$ disruption (cf. section III. A. 1 for discussion of the display.)

776131
 Fig. 4. Amplitude and phases [raw (open circles) and geometrically-corrected (closed circles)] for the $m = 2$ $n = 1$ oscillation.

773740
Fig. 5. Line integrated and inverted local profiles for the two orthogonal mode components.

776130
 Fig. 6. Equilibrium (line) and reconstructed elliptical profiles (dashed) for the $m = 2$ mode at 174 msec, prior to disruption.

773745
Fig. 7. Contours of equal x-ray emissivity for the $m = 2$ mode.

776128
 Fig. 8. Equilibrium (line) and reconstructed elliptical profile (dashed) for the $m = -2$ mode at 178 msec, immediately after disruption.

776127
Fig. 9. Superposition of equilibrium profiles before (open circles) and after (closed circles) disruption.

776137

Fig. 10. Line-integrated traces at 17 radial positions showing the $m = 2$ and $m = 1$ precursor oscillations and the $q = 1$ disruption.

776142
Fig. 11. Faster oscillations and disruption at tangent radii (a) 0 cm; (b) ± 4 cm; (c) ± 8 cm.

Fig. 12. Mini-disruption with $m = 2$ precursors and location inside the $q = 2$ radius.

776138

776135

Fig. 13. Line-integrated traces showing the $m = 3$ mode and disruption at an inner radius.

776129
 Fig. 14. Abel-inverted equilibrium emissivity profiles before (hollow) and after (peaked) on $m = 3$, $n = 1$ minor disruption.

776139

Fig. 15. Line-integrated traces showing a disruption with no apparent fluctuations.

776125
Fig. 16. Central line-integrated x-ray emissivity for a high density helium discharge with a major disruption.

Fig. 17. Profiles of electron (a) temperature and (b) density after final sawtooth and before major disruption.

776141

776133
 Fig. 18. Line-integrated traces for a high density helium disruption showing precursor oscillations and the disruption itself.

776136

Fig. 19. Precursor oscillations in high density helium disruption.

776134

Fig. 20. High density helium disruption.

776143
 Fig. 21. Superposition of traces at (a) $r = 0$ cm, (b) ± 2 cm, (c) ± 4 cm, (d) ± 8 cm, and (e) ± 12 cm during the disruption.

776126
Fig. 22. Central line-integrated emissivity for a high temperature discharge with a major disruption.

776124

Fig. 23. Line-integrated traces of the high temperature disruption.