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Critical Issues and Experimental Examination on Sawtooth and Disruption Physics

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Abstract

The catastrophic phenomena which are associated with the major disruption and sawtooth contain three key processes: (1) Sudden acceleration of the growth of the helical deformation, (2) Central electron temperature crash, and (3) Rearrangement of the plasma current. Based on the theoretical model that the magnetic stochasticity plays a key role in these processes, the critical issues and possible experimental tests are proposed. Present experimental observations would be sufficient to study the detailed sequences and causes. Though models maynot be complete the comparison with experiments improves understandings.

Keywords: Sawtooth, Major Disruption, Magnetic Stochasticity, Trigger, Energy Quench, Tokamak, Experimental Test

I Introduction

Much has been contributed from JET to the recent progress in the understanding of the sawtooth physics. The observed variety of the sawteeth (as in Fig.1) with the measurement on q(0) after the crash (q(0)is often observed to be less than one[1]) have required a new picture which is neither the Kadomtsev model nor the Wesson's low shear model[2]. [Experimental data on q(0;t) from TEXTOR is shown in Fig.2[3]. JET has shown that[4] q(0)= 0.7 ± 0.2 and $\Delta q(0)^{collapse}=0.03\pm0.02$ and confirmed TEXTOR picture (not necessarily for all collapses but at least for some collapses in JET).] The finding of the 'magnetic trigger' in which the growth rate of the m=1 mode abruptly becomes the order of MHD growth rate[5] (as in Fig.3) has provided a new touchstone of the sawtooth modelling.

We conjecture that the three processes, i.e., the central temperature crash, 'magnetic trigger' and the magnetic flux rearrangement, which are tightly connected but can have different time-spatial scales, are the key concepts of the catastrophic events in tokamaks (major disruption, sawtooth, High-beta collapse, some of Giant ELMs and so on). This proposed task is to examine the experimental data (on JET, and on JT-60/JFT-2M if possible) on sawtooth and major disruption from this point of view, study the sequences and search the cause in the catastrophic phenomena. Standing on this view, we have recently proposed theoretical models on the sawtooth[6] and major disruption[7]. The rough sketch is given in next sections.

We here list some of the critical issues and the key experimental observations, that would be the touch stones for the physics picture of the catastrophic events. On occasion of Dr. Campbell's visit to JAERI, we would like to propose a collaboration on the physics of the sawtooth and major disruption. For these progresses which came out from JET, Dr. Campbell has been one of the main promoters. By identifying the critical issue and possible tests, the data analysis would be more prompt and the clear test on the physics picture would be possible.

In the following, the key idea is explained, the necessary data is highlighted by the *italic* letter and relevant observations are discussed.

II Sawtooth Physics

(2.1) Modelling

The modelling has been published in Ref.[6].

The experimental key points are

(E1) There is a variety in the temperature collapses; full fast crash, partial fast collapse, and slow partial collapse.

(E2) There is a variety in the helical evolutions: precursor growth, saturated m=1 oscillation, post cursor.

(E3) The growth rate of the m=1 perturbation changes abruptly before the onset of crash.

(E4) q(0) is often below 1 during the whole period of sawtooth cycle.

To cope with these observations, the theoretical model has been developed that

(T1) Stochastic layer is formed, which is wider than the m=1 island width itself. The temperature crash occurs when the stochastic layer touches the axis, while the flux rearrangement ($q(0)\rightarrow 1$) happens when the island reaches the axis (Fig.4). They are different phenomena and have different time scales. The full temperature crash can be possible even if the q(0) is kept below one.

(T2) Stochasticity of the magnetic field can accelerate the growth of the m=1 mode. There is a threshold amplitude of m=1 mode for the onset of rapid growth.

(T3) After the onset of stochasticity-driven, rapid growth of the m=1 mode, the mode can be stabilized by an enhanced viscosity. This stabilization is easier for high density plasma. The condition discriminating the 'fast full $T_{e(0)}$ collapse' and 'fast partial collapse' is approximately given

$$[\ell(0)-1]^{0.4}\varepsilon^{-0.8}R_m{}^{-1.2}n_{20}{}^{-0.8}T_{keV}{}^{-0.2}B_T{}^{0.4} < 1.$$

(Inequality for the partial temperature collapse.)

Figure 5 illustrates the dynamic trajectories of various kinds of the sawtooth oscillations.

The prediction of the model, which can be tested by the experimental data includes:

(1) the threshold amplitude for the onset of the rapid growth,

$$\tilde{B}_r R/r_1 B_t > 0.07[\ell(0)-1],$$

(2) the density dependence of the variety of sawteeth. (The equation in(T3).)

So long as we see the IAEA paper of JET[5)], the threshold amplitude is such that [helical shift of axis $\simeq$ 3cm], which is in the range of our prediction. ('Threshold amplitude' is illustrated by hatched region in Fig. 3)

(2.2) Future Experimental Investigations

To study the physics picture of the crash mechanisms, we have the following questions.

(Q1) *Is there any experimental observation on the threshold amplitude? In particular:*

- *Is there any information on the difference of the threshold amplitude in low-shear and high-shear cases?*
- *Is there any information on the dependence of the threshold amplitude on the inversion radius?*

(Q2) *Is there any experimental observation on the density dependence of the rapid growth rate before the crash?*

(Q3) *Is there any evidence that, at high density, fast partial collapse is more abundantly observed compared to the fast full collapse?*

Assuming that there has not been a systematic study on these point, a candidate of the relevant data will be;

(D1) To collect data for displacement ξ near the magnetic trigger. [To study the correlation between the threshold amplitude and the resultant growth rate with plasma parameters, inversion radius and q(0) value.]

(D2) To collect data for the appearance of kinds of sawteeth (fast full, fast partial slow partial···). [To study the correlation of the observation probability with plasma parameter.]

(D3) The effect of fast ions is also the important issue, so that these study is suitable for the shots in which fast ions are confined much.

(D4) The 'Fourier' $T_e(r,t)$ data near the q=1 surface. To correlate $\nabla T_e(r_1)$ just before crash with the occurrence of the full fast collapse or the long-lasting precursors. [One of the authors (ST) has once studied this relation during his stay at JET.]

In addition to these, Dr. Wesson has quoted an experimental data on the neutron sawtooth during the flat top of the monster sawtooth[2)]

(Q4) *Does JET have made some progress or conclusion on this problem?*

III Physics of Major Disruption

(3.1) Modelling

We have developed the similar idea for the major disruption[7]. The rough sketch is as follows. (See Fig.6)

(T1) m=2 island can cause stochastic layer around itself (which is well known), and this stochasticity can lead explosive growth of the mode when the mode amplitude exceeds a certain critical amplitude, the line (3) of Fig.6 (which is a new result).

(T2) As is the case of sawtooth crash, the stochastic layer reach the center [line (2) of Fig.6] before the m=2 island touches the axis [line (1) of Fig.6]. This means that the temperature crash occurs before the replacement of the magnetic flux (internal inductance change) occurs.

(T3) One possibility to cause the the explosive growth is the coupling of the m=2 and m=1 mode.

(T4) Sequence in the major disruption event is as follows:

1 {Slow growth of m=2 mode}

2 Sudden fast growth of m=2 mode coupled with m=1 mode, which is also observed as

3 Sudden drop of $T_e(0)$ [Energy quench]

4 Partial loss of plasma energy

which can occur with small time delay after 4, and be studied by observing the heat local onto limiter/divertor

5 Start of the axisymmetric motion of the plasma column

which is observed by the feedback action of the equilibrium coils

6 Rearrangement of the core magnetic flux (complete reconnection) and change of internal inductance

which is associated with the poloidal magnetic energy. This also accelerates the axisymmetric motion of the plasma. Order of the processes 4-5 and 6 can be interchanged.

7 Change of the internal inductance causes the skin layer near edge.

Figure 6 illustrates the situation (quoted from Wesson paper[8], in which authors call this 'Magnetic flux trap'.) At this moment, the change of the poloidal field cannot be transmitted to the surface, due to the persistent magnetic surface near the edge.

8 Generation of the run away electrons by the trapped flux

The strong negative voltage is trapped in the peripheral plasma, which typically has the temperature of 500eV to 1keV, generates the run away electrons.

9 {Plasma wall interaction can enhance impurities, which reduces the plasma conductivity.}

10 Radiation cooling causes the final drop of temperature, leading to very high resistance, by which the negative loop voltage is diffused to the surface. [Negative loop voltage]

11 Reduction of plasma current [Current quench]

12 Positive voltage spike and generation of run away electrons

Processes 8 and 12 generates the run away electrons, but the direction of fast electrons are reversed.

Processes 1 and 9-12 are conventional arguments. Discussions on the operational conditions for the occurrence of the major disruption, such as the density limit (roles of MARFE and detachment), locked mode, current profile, and impurities, are made on the process 1. The main interest for the modelling is to investigate the catastrophic phase of the event precisely.

(3.2) Experimental Investigations

This model needs an experimental test such as

(Q1) ***Have you studied the change of the growth rates of m=1 and m=2 modes before the onset of the energy quench of the major disruption?***

Recall your study on the sawtooth. The sudden acceleration of the mode growth is expected. Figure 23 of JET paper[9) (Nucl. Fusion **29** 641) [quoted as Fig.7 here] indicates that the m=1 motion near core occurs abruptly. The other evidence is seen in Fig.30 of JET paper (Nucl. Fusion **29** 641) [quoted as Fig.7 here] that the n=1 amplitude grows abruptly a few ms before the onset of the current change. These can also be analyzed in the context of the 'magnetic trigger'.

(Q2) ***In the data by which you talk about the 'm=1 erosion', have you studied the dynamics of the m=2 mode?***

We expect that in one of the arrays (toroidal or vertical arrays), the rapid growth of the m=2 mode is observed. Figure 24 of JET paper (Nucl. Fusion **29** 641) [quoted as Fig.8 here] shows that the noticeable m=1 deformation starts between the time of lines 5 and 6, but the sudden drops at 2.5m and 3.2m occurs in between the time of line 4 and 5. On seeing the other data (shot 6942, time 8.768sec-8.773sec, see also Fig.8), we notice the rapid change of m=2 at t=8.7688sec, just before the onset of m=1 deformation ('erosion').

The other evidence is seen in JIPP T-II

experiment[10] (see Fig.9).

(Q3) *Have you ever studied the q(0) value before the onset of energy quench? (More specific: q(0) at or just before the start of 'erosion'.)*

(JIPP T-II has shown that q(0) may be above one just before crash. Theory has shown that the coupling of m=2 mode with m=1 mode leads violent instability when q(0) is above unity. See Fig.10.)

(Q4) *Have you the experimental data about the order of occurrences of the energy quench and axisymmetric plasma motion (or, equivalently, the charging of the vertical field to keep the plasma position)?*

(Our model discriminates the occurrences of the energy quench and the change of the internal inductance. Energy quench first, and q-profile change follows.) If the energy quench is associated with the rapid loss of electrons out of the plasma, the change of the plasma energy leads the change in equilibrium position. Data from TFR (Fig.10) suggests that the horizontal motion follows the energy quench very rapidly. What happen in large devices? We notice in TFTR experiments, though it is high beta disruption, the occurrence of the violent activity in $T_e(0)$ precedes the global energy loss by the amount of $\propto 100\mu s$ (Fig.11).

(Q5) *Have you a clear data that the axisymmetric plasma* *motion, after the energy quench, starts before the negative loop voltage spike?*

Is there any data that the axisymmetric plasma motion occurs after the energy quench, and before the negative spike?

The delay of the negative voltage spike after the occurrence of $T_e(0)$ crash were studied on JET. [See Fig.29 of JET paper (Nucl. Fusion **29** 641) which is quoted as Fig.12 here.]

We divide three processes, as written in (3.1), and their causality as follows. The central T_e crashes first. (Plasma starts to move inward if some of the electron energy goes out of the plasma column.) Then the magnetic island reaches the axis, causing the flux rearrangement and the change of the internal inductance. The plasma can move inwardly due to the change of the hoop force. The rearrangement of the flux may be limited in the core because the magnetic surface near edge is still nested, as Dr. Wesson has discussed in his paper of the 'flux trap'[8]. The negative spike is trapped near edge, as is shown in Fig.12 and magnetic diffusion time will be necessary for this trapped flux to reach the surface.

(Q6) *Have you observed the generation of the runaway electrons before the negative spike is observed?*

If the magnetic flux trap works, and the negative voltage spike is first trapped between the destroyed magnetic regions and edge layer in which the magnetic surfaces are complete, strong negative electric field exists in the plasma. Dreiser limit can be easily exceeded.

(Q7) ***In other words, is the directionality of the hard X-ray studied on occasion of the major disruption?***

The trapped negative voltage accelerates the electrons in the co-direction to the plasma current. On the other hand, the conventional process which generates the run away electrons at the current quench is the positive loop voltage caused by the current reduction. This process produces the run away electrons which are accelerated in the direction counter to plasma current.

[We note that the former acceleration can also be a serious problem although the volt•second of the negative voltage spike is usually smaller than that of the positive voltage spike. This is because the small resistance due to the high electron temperature. These two processes lead the different parameter dependences of, say, the maximum energy of the run away electrons. For extrapolations, both must be examined.]

IV Summary

Proposed picture for the catastrophe contains three key physics processes:

(1) Sudden acceleration of the growth of the helical deformation

(2) Central electron temperature crash

(3) Rearrangement of the plasma current.

Depending on the magnitude of the change in the equilibrium quantities, the result may reach full plasma disruption or remain partial change.

These three aspects are crucial in examining the physics of the major disruption and sawtooth, in particular in understanding the catastrophic dynamical nature of the events. The discussed models may or maynot be correct, but can serve for the working hypothesis to see the data. Present experimental observations would be sufficient to study the detailed sequences and causes. The collaboration would be very fruitful.

Acknowledgements

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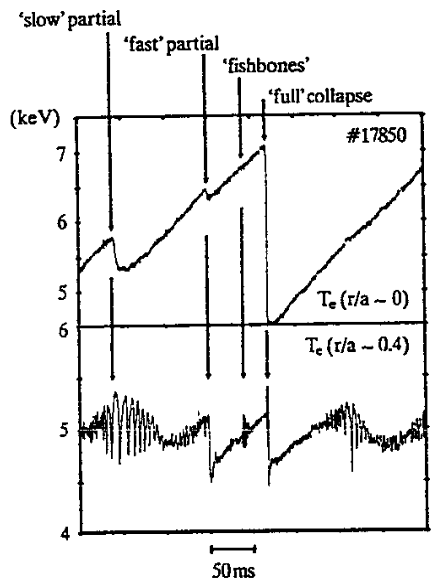
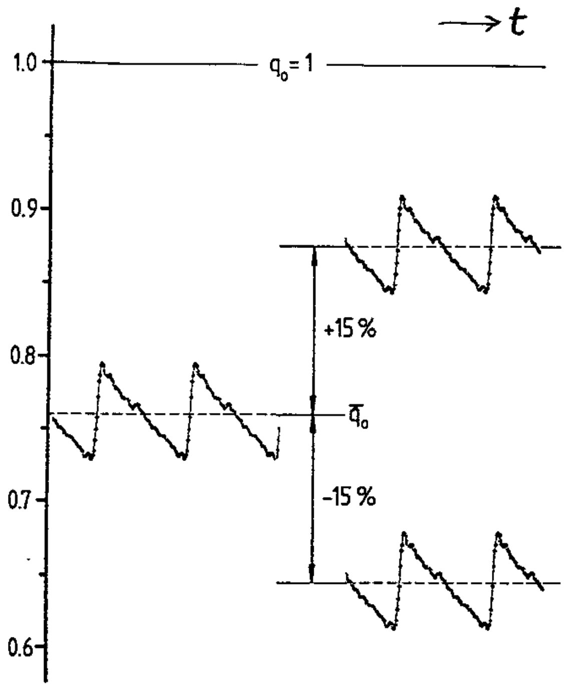
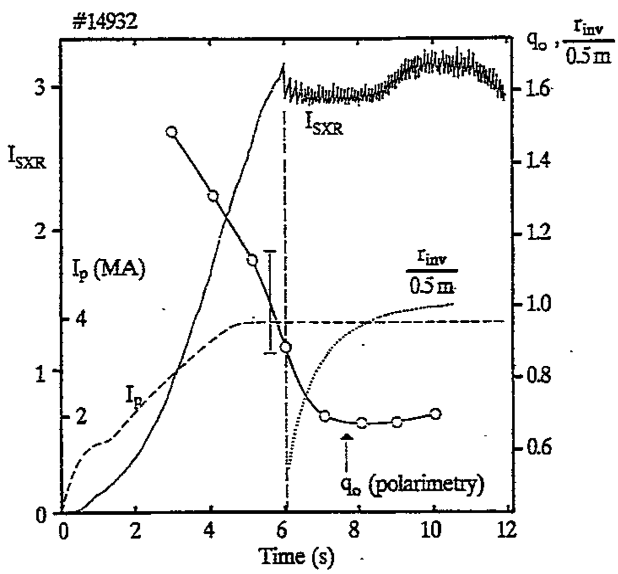


FIG. 1. Behaviour of the electron temperature at two radii during a sawtooth cycle in a JET discharge with auxiliary heating. The major commonly observed phenomena are indicated.

Fig.1 Variety in sawtooth crashes (quoted from IAEA Nice paper)





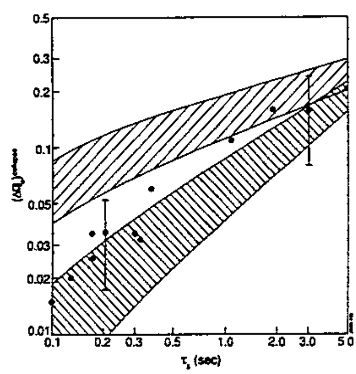


Fig. 4--Change in q_o versus preceding sawtooth period. Circles--data, upper band--field diffusion calculation assuming complete reconnection, lower band--field diffusion calculations assuming $q_o = 0.75$ following the sawtooth collapse.

Fig. 2 Temporal change of q(0) during the sawtooth cycle (TEXTOR: quoted from ITER database workshop), the development of q(0), and the change of q(0) after the crash (O'Rourke paper).

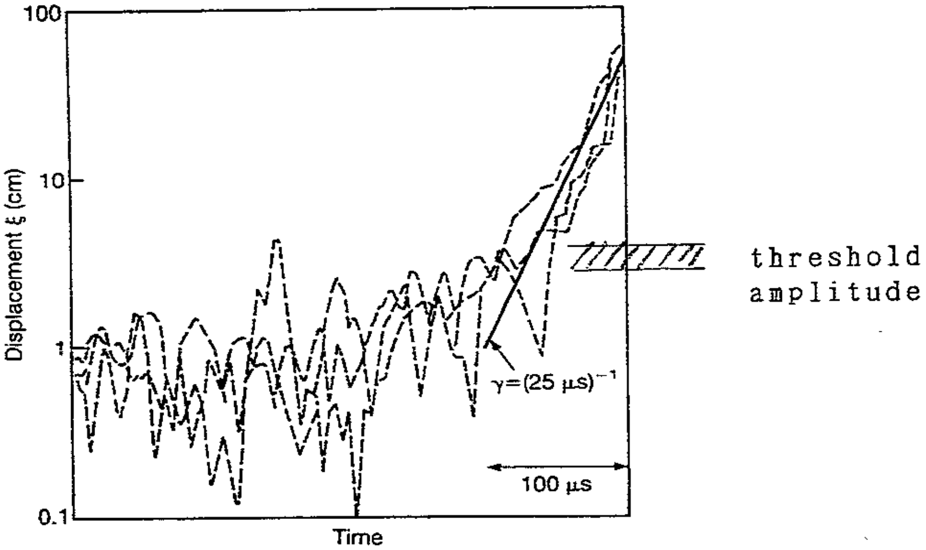


FIG. 3. Displacement of the soft X-ray emission peak, derived from two-dimensional tomographic reconstructions, during fast sawtooth collapse. Experimental results for three cases are illustrated. The data show that a growth rate of (25 μs)$^{-1}$ is achieved even before the displacement is large enough to be detected above the experimental noise.

Fig.3 'Magnetic Trigger' observed on JET (quoted from IAEA Washington paper)

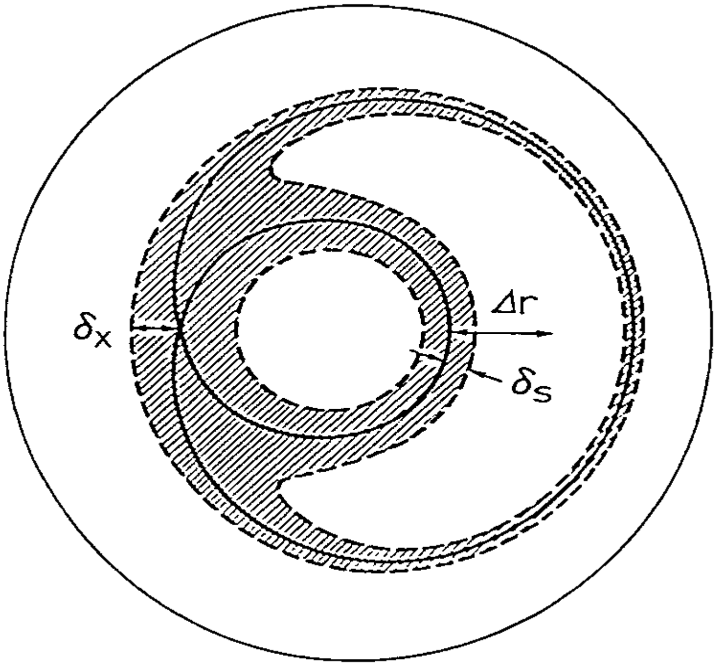


Fig.4 Development of the stochastic magnetic region (hatched) around the m=1 island. Hatched region can reach the axis <u>before</u> the island touches the axis.

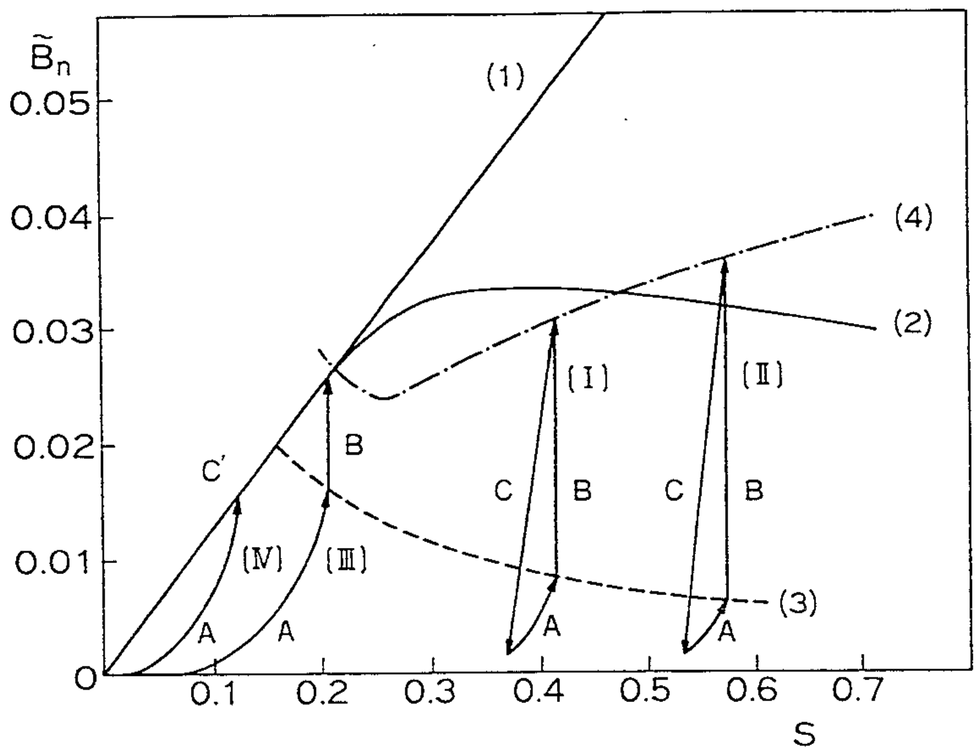


Fig. 5 Four types of sawtooth oscillations are shown in the plane of normalized helical perturbation $B_n = \tilde{B}_r R / r_1 B_t$ and shear $s = \iota(0) - 1$. When B_n exceeds line (3) stochastic acceleration of the mode takes place ('Trigger'). At line (4), the growth stops. Line (2) indicates the condition that the stochastic region come to the axis ('temperature collapse'). Line (1) denotes that the island touches the axis ('magnetic reconnection').

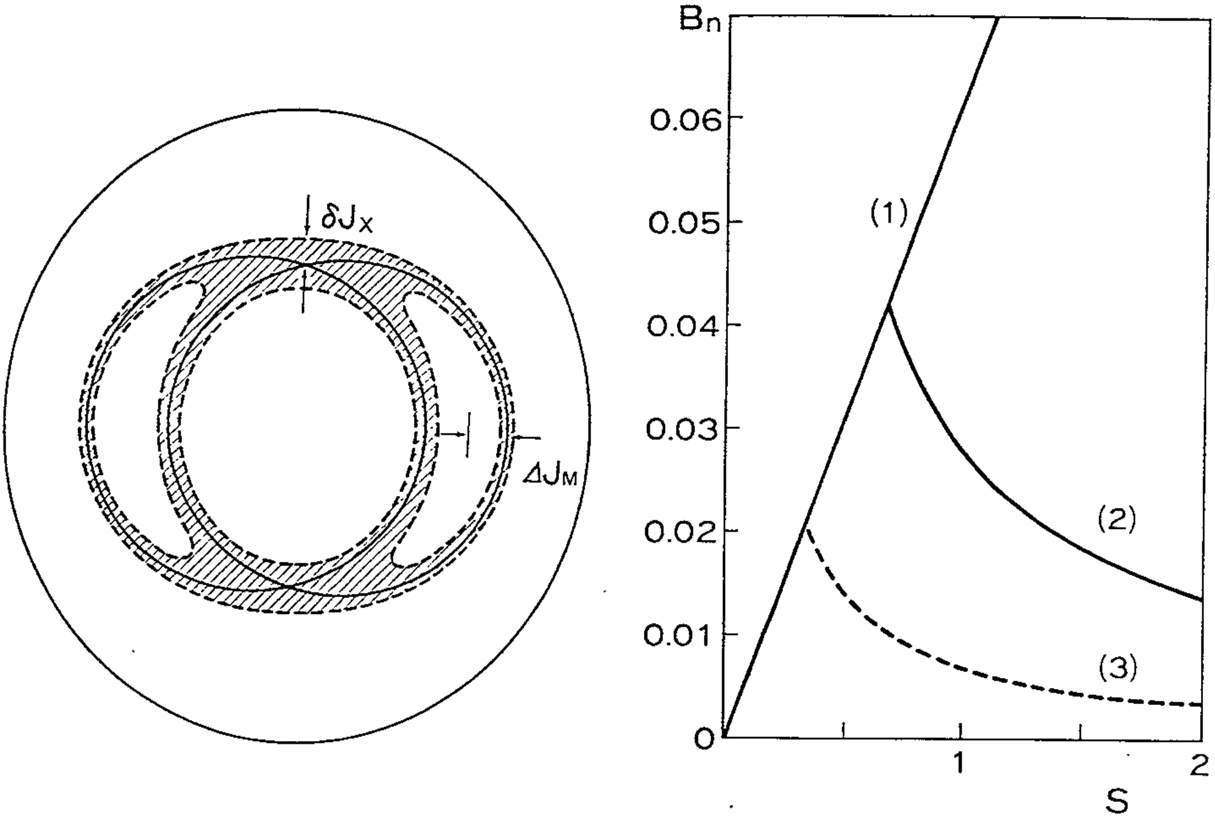


Fig. 6 Formation of the stochastic region around the m=2 island. The conditions for the stochastic acceleration for the growth, [line (3), 'the trigger'], the stochastic region touches the axis [line(2), 'energy quench'] and the magnetic island touches the axis [line (1), magnetic reconnection] is shown. $B_n=2\tilde{B}_r R/r_2 B_t$ and $s=rq'/q$.

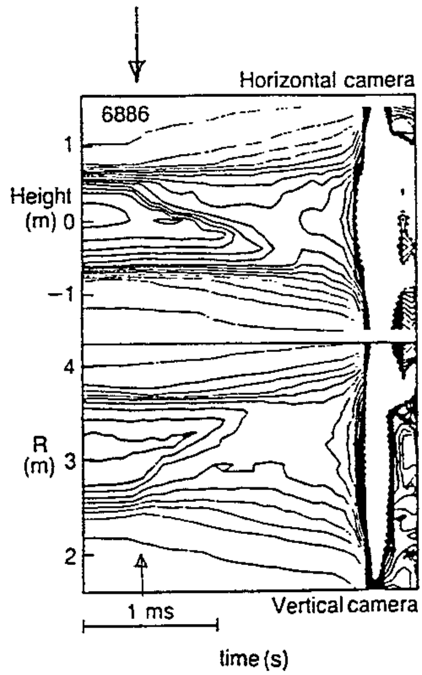


FIG. 23. Contour plot of X-ray camera signals versus position and time just before the major disruption. The fast spike at the end is above the highest contour.

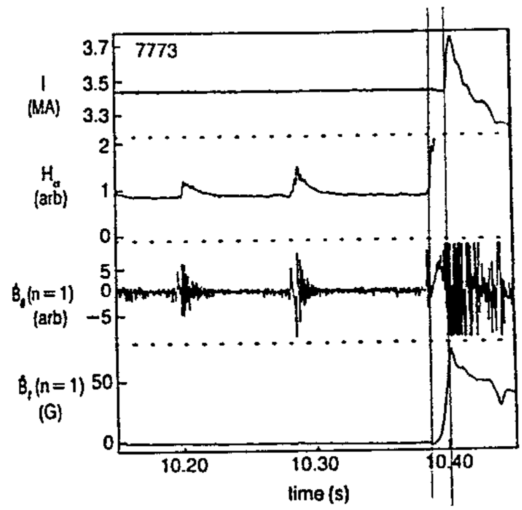


FIG. 30. Time behaviour of plasma current, H_α, $\dot{B}_\theta$ (n=1) and $\tilde{B}_r$ (n=1) before a major disruption at low q. Sawteeth are present at t=10.2 s and 10.3 s.

Fig.7 Evolution of the m=1 deformation before the energy quench and current quench. Fig.23 and 30 of JET paper (Nucl. Fusion **29** 641). Shot 6886 shows that the magnetic trigger of n=1 mode occurs (the arrow added). Shot 7773 indicates similar phenomena.

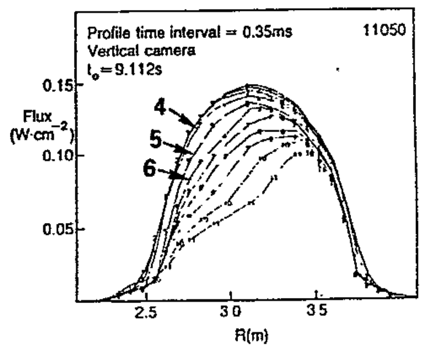


FIG. 24. Radial profiles of X-ray signals, showing the profile erosion. The flux for each line of sight is plotted against the radius of its midplane intersection.

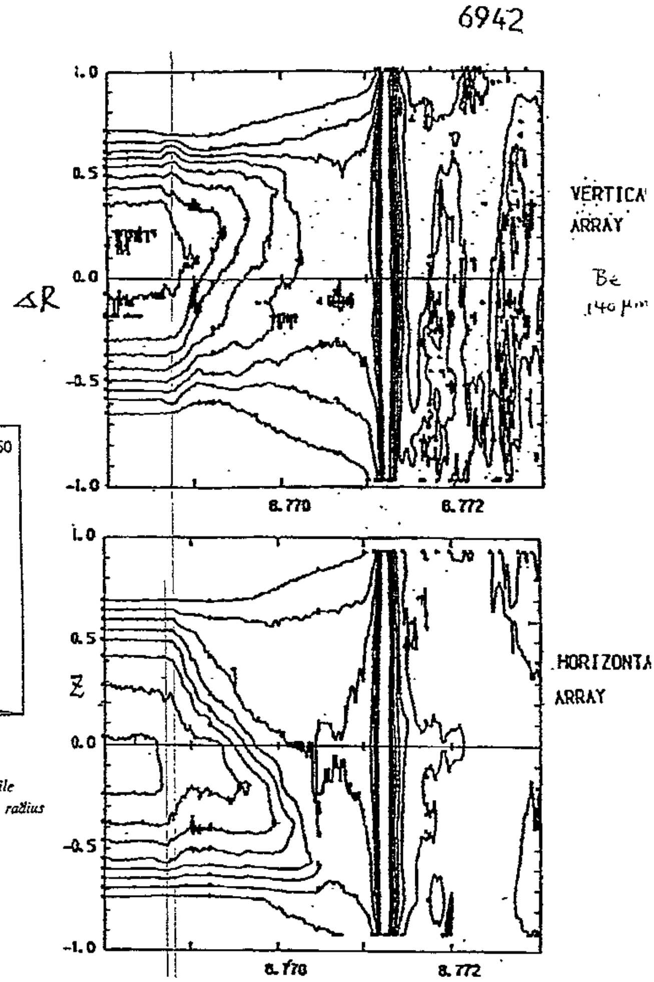


Fig.8 Magnetic trigger for m=2 mode. Fig.24 of JET paper (Nucl. Fusion **29** 641) shows that the reduction at R=2.5-2.6m precedes the m=1 erosion. Shot 6942 indicates the m=2 grow before/at the start of erosion. (Around t=8.7687sec. Peak time in vertical array and that in horizontal array seems to differ by the amount of 100μsec, suggesting that the signal is not m=0 but m=2.)

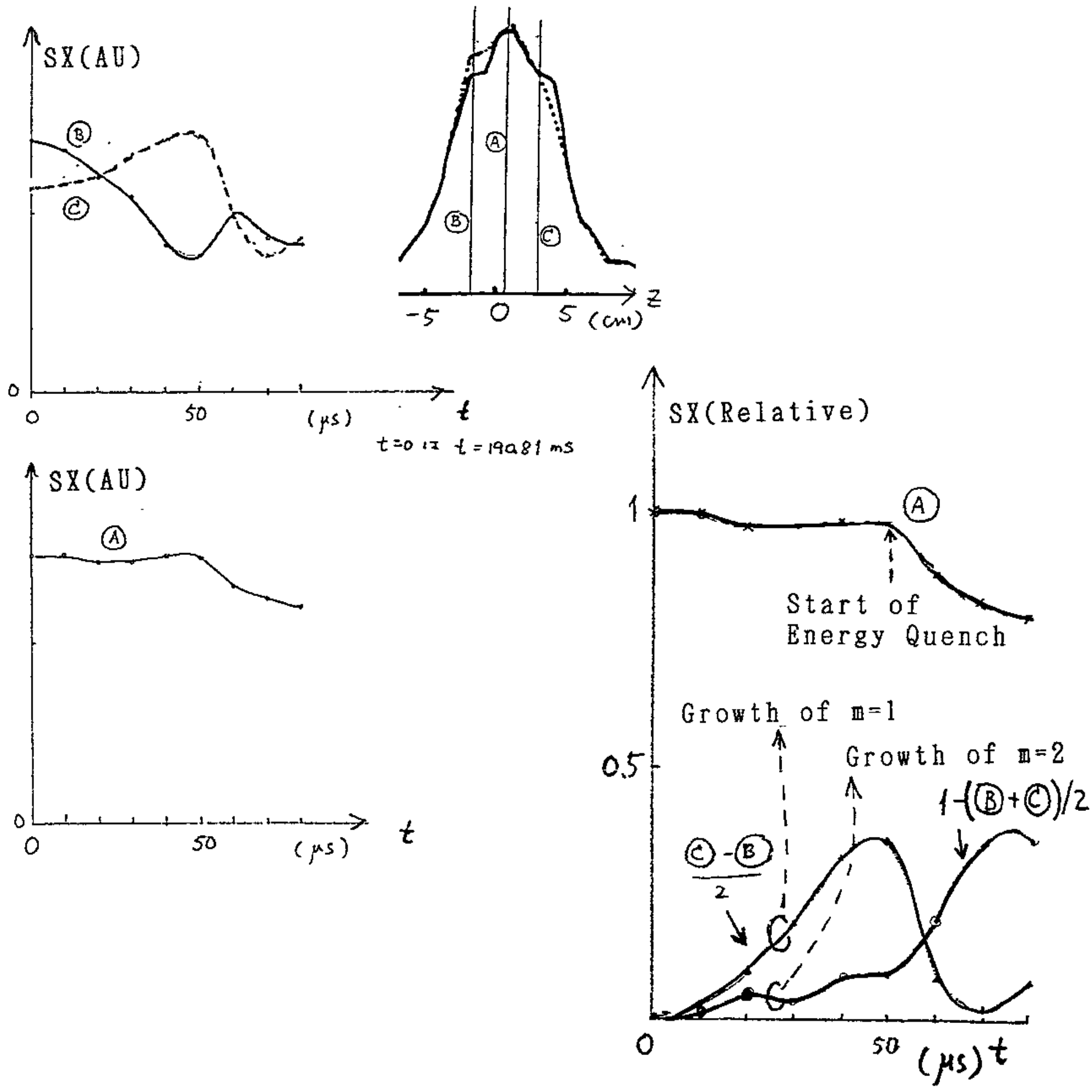


Fig.9 Fast observation of the SX array in JIPP T-II experiment (Tsuji paper*). Temporal evolutions of cord signals A, B and C (t=0 is chosen as 190.81ms after the start of discharge). Signals are normalized to the values at t=0, and relative amplitude are plotted; A, [C-B]/2 and [B+C]/2-1 (related to the central temperature crash, m=1 mode and m=2 mode, respectively.) Growth in m=1 and 2 occurs in the time scale of a few tens of μs, and the central temperature crash occurs after 50μs.

(* S. Tsuji, et al.: Nucl. Fusion 25 (1985) 305.)

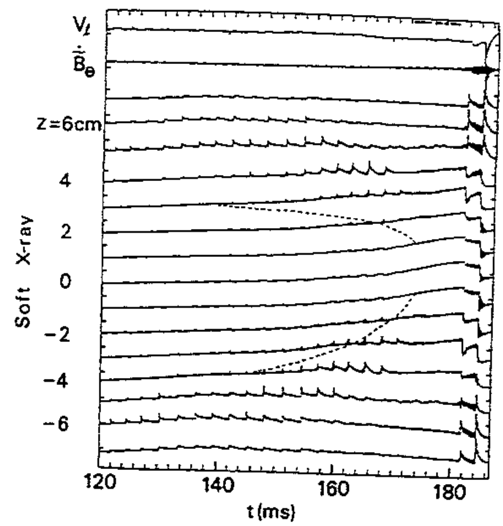


FIG.3. Soft-X-ray traces, showing the peaking and disappearance of sawtooth activities in a high-density discharge. The broken line indicates the location of phase inversion of the sawteeth.

Fig.10 Before the disruption takes place, the sawtooth inversion radius gradually shrinks and disappears, implying q(0)exceeds unity. Observation on JIPP T-II[10].

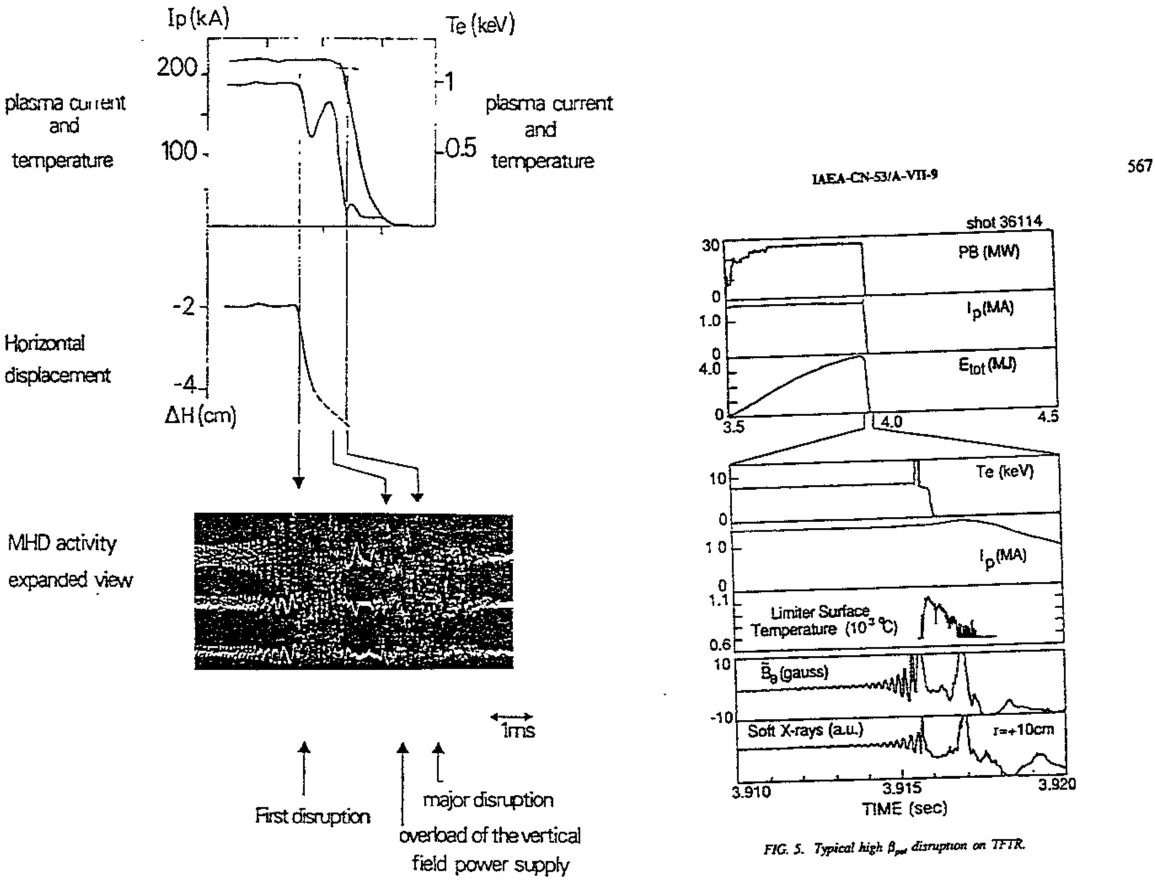


Fig.11 Observations on TFR tokamak[11]. Horizontal displacement takes place at the onset of the energy quench. Some event occurs for the central electron energy about 100μsec prior to the energy deposition onto the limiter (TFTR)[12]. Plasma energy loss occurs when the limiter temperature starts to grow. In both cases, magnetic trigger phenomena are seen.

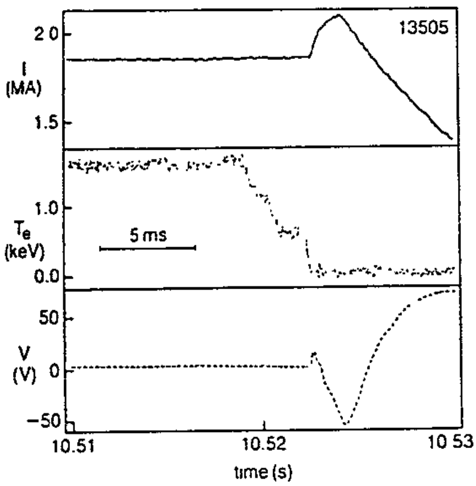


FIG. 29. Current increase, temperature drop and negative voltage spike during a major disruption.

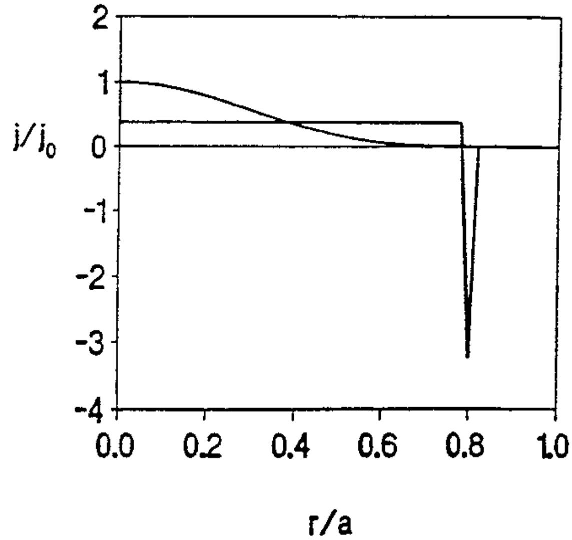


Fig.12 Fig.29 of JET paper (Nucl. Fusion 29 641) shows that the time difference between the energy quench and the negative loop voltage. Discrimination between these two is difficult in TFR data, suggesting that the size effect of the event. Schematic drawing of the current profile after the current redistribution (in between the energy quench and the negative loop voltage.)

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