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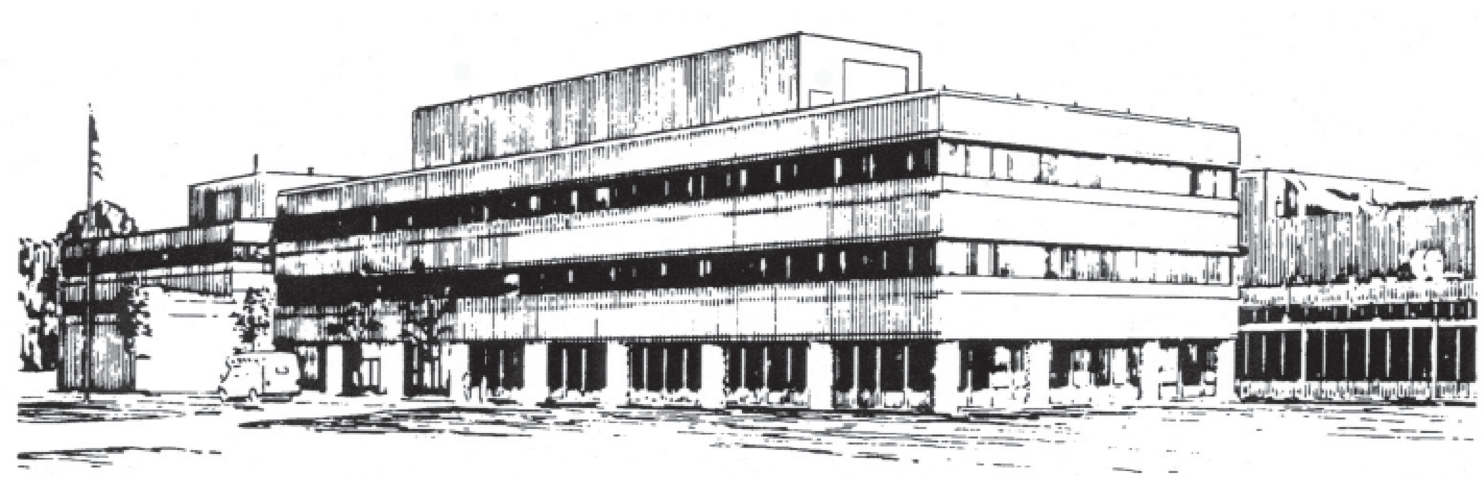

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PHENOMENOLOGY OF INTERNAL RECONNECTIONS IN NSTX

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ABSTRACT

The behavior of large scale MHD-modes was investigated in the National Spherical Torus Experiment (NSTX) during Reconnection Events (RE) using combined analysis of magnetic probe signals, and Soft X-Ray (SXR) data. The comparison of mode dynamics during precursor and disruption stages in T-11M (small circular plasma), TFTR (large circular plasma), and NSTX (large spherical plasma) was done. The analysis shows that the sequence of events of minor and major IRE's in NSTX is essentially similar to that for disruptions in moderate aspect ratio tokamaks. The main feature of disruption dynamics apparently affected by small aspect ratio in NSTX appears in the relatively slow thermal quench event (5-10 times longer compared to ordinary tokamaks), which precedes the major IRE. The coincidence of the electron and neutron quench times during the major IRE leads us to the conclusion that the fast ions and hot electrons leave the center of a plasma column simultaneously, i.e. convectively.

INTRODUCTION.

It was found in the first experiments on START [1] that a typical feature of small aspect ratio tokamaks (A=R/a < 2 - spherical torii - ST) is the practical absence of disruptions with current quenches. In particular, it is found that in an ST the major disruption is transformed into a local phenomenon, which is accompanied by an insignificant loss of poloidal magnetic flux. It has received the special name - Internal Reconnection Event (IRE).

A clear understanding of the physical nature of IRE's may be useful for the elimination of disruptions and mitigation of their consequences in tokamak - reactors with moderate and large aspect ratios (> 3).

The purpose of this work is to compare the basic behavior of MHD-activity before and in the process of an IRE in a small aspect ratio tokamak, NSTX with the similar phenomena (disruptions) in the normal aspect ratio tokamaks TFTR [2,3] and T-11M [4] where A is ~ 3.

As expected, the basic difference between ST's and usual tokamaks will be in the different interaction of external and internal MHD-activity. The external MHD activity is measured by magnetic probes near the plasma edge and the internal activity by Soft X-Ray radiation (SXR) from the center.

The dynamics of external and internal large scale MHD was analyzed in ohmic and Neutral Beam Injection (NBI) heated discharges. It was found, in general, that the MHD activity in NSTX has the same basic features as were observed in START and in major disruptions in ordinary tokamaks.

A typical example of an IRE (shot #103043, t = 220ms) with small change of plasma current (similar to what was seen in START) is given Fig. 1a. Fig. 1b (shot #103329) shows another example of stronger phenomenon. Here the IRE is followed by a current quench, similar to what frequently occurs in ordinary aspect ratio tokamaks.

To distinguish these cases we shall name the events of the first type - minor IRE, and second one - major IRE.

EXPERIMENTAL CONDITIONS.

The internal MHD-activity was measured by 3 sets of SXR detectors (16 vertical and 16+16 horizontal chord channels. Fig. 2 [5]). The vertical set of SXR detectors had an 0,3 μm Ti foil and can measure hard ultraviolet (0,1-2 keV) and SXR (1-10 keV) radiation. Two horizontal sets had 10 and 100 μm Be foils and measured only SXR. The different spectral ranges complicated the interpretation of our observations and did not allow for the application of tomography. However, the overlapping of several horizontal channels of different spectral ranges allowed an estimate of the electron temperature in the plasma center. In the shot #103043 (Fig. 3d), for example, Te(0) was approximately 0.5 keV with little variation up to the IRE development. However, top and bottom horizontal SXR signals could be matched or scaled at the center for SXR-mapping (visualization). Visualization of the vertical and horizontal chord signals during a minor IRE is shown in Fig. 3e,f. The visualization method allows us to make some conclusions about the structure of internal perturbations. Namely, in this case, the relative phase shift indicates that the internal IRE precursor had, in general, an m=1/n=1 structure, where m is the poloidal, and n is the toroidal number of the helical perturbation (Fig .4).

The external magnetic perturbations (Fig. 3 b, c) were measured by sets of poloidal (12) and toroidal (12) BΘ magnetic probes placed inside the vacuum chamber. Unfortunately, the diagnostic ports and vacuum chamber elements did not allow placing magnetic probes equidistantly. In particular, the poloidal set of fast magnetic probes gives us only qualitative information about the structure of MHD perturbations because it covers only the outboard area 20-80 degrees above and below the midplane in the poloidal direction. The toroidal set of magnetic probes allows an estimate of the n numbers of edge magnetic perturbations.

DEVELOPMENT MHD-PERTURBATION IN MINOR IRE

As seen in Fig. 3, the m=1/n=1 precursor of minor IRE has almost constant amplitude for 10 msec. However, the behavior of non-central SXR channels shows that during this time the area of the perturbation expands, i.e. the positive SXR perturbation (hot spot) moves to large minor radius. EFIT data (Fig. 1a) shows that during this time q(0) and q(r) near the plasma center remain above 1. The long, steady existence of a positive T_e perturbation in the region q(r)>m/n=1 is possible, if it has the character of a “positive magnetic island” [6]. In this case there is an expanding force along r probably responsible for the perturbation expansion. The rotation period of the SXR perturbation slows down, becoming a Locked Mode. This condition exists for about 2 msec, and then the internal crash with the pulse of peripheral UV- radiation happens (Fig. 3f). That could be a consequence of peripheral impurity radiation caused by energetic electrons streaming out from the center, causing impurity influx from the wall.

Magnetic perturbations near the plasma edge (Fig. 3 b, c) repeat the behavior of peripheral SXR channels, namely, they nonlinearly grow as the internal perturbation expands.

The main component of the magnetic perturbation is n=1, and the amplitude is poloidally localized near the torus equator. Analysis of poloidal magnetic probes shows that as the internal perturbation expands, the poloidal localization of the external magnetic perturbations becomes broader (Fig. 3 b, c).

We notice that the total plasma current Ip, during the growth of the SXR perturbation increases slightly. That can be the result of a reduction in internal inductance, li, i.e. the current distribution is flattened. The crash of SXR signals is accompanied by an appreciable increase of Ip (~ 4 %). That means a further drop of li and emission of a part of the poloidal magnetic flux from the central areas. All of these events have features similar to minor disruptions in normal tokamaks, although it seems that the process in NSTX is slower. The circumstance that a minor IRE does not result in a current quench strengthens this analogy. Accordingly, the major IRE (Fig. 1b) should be compared with the major disruption.

DEVELOPMENT OF MHD-PERTURBATIONS IN MAJOR IRE

Fig. 5 shows the last phase of a major IRE with current quench (Fig. 1b, shot #103329). Analysis of SXR signals (Fig. 5 c, d, e) shows that the IRE in this case is preceded by the spontaneous development of a locked mode (LM) (phase I). It collapsed (phase II) after 5 ms with transport of energy (deduced from SXR radiation) into external areas. This crash of SXR emission in the center is accompanied by a collapse of electron temperature, i.e. erosion (flattening) of the Te(r) profile and looks like a conventional fast thermal quench (deep internal disruption) which precedes the major disruption in tokamaks. Following it, in phase III, the amplitude of the edge MHD activity (Fig. 5b) and penetration of impurities from the wall to plasma (Fig. 5e, UV+SXR) increases. The plasma current, Ip at first begins to increase, which could be a consequence of current channel expansion as a result of central cooling, and then it falls. This current quench, apparently, is accompanied by vertical instability of the plasma column (VDE). The SXR mapping (Fig. 5 d, e) shows, that during the current erosion a hotter area (secondary hot spot) is formed in the cold plasma region with the center displaced downwards and outside. Next the current spike appears during the IRE, which destroys the secondary hot spot. Such behavior of the plasma column is typical for elongated tokamaks in the case of major disruptions with the loss of vertical stability. It is usually caused by cutting of external areas of the current channel by the wall or impurity radiation. The narrowing of the current channel initiates the new disruption with the development of the m=1/n=1 mode, as a rule [2]. The current channel expansion during disruption (the decrease of internal inductance) generates a new current spike.

DISCUSSION. COMPARISON WITH TOKAMAKS

The comparison of major IRE in NSTX with the major disruption in tokamaks with A>3, shows many common features. In particular, in TFTR [2], the major disruption (Fig. 6) follows the minor disruption (1st quench), beginning with a fast cooling of the column center(10 ms quiescent phase), then the fast erosion and displacement of the Te(r) profile during 100 μsec (2nd quench) and the generation of a positive current spike. The evolution of Te(r) during the quiescent phase shows, that during this time the current channel was narrowed. The fast, (during the 100 μsec) Te(r) profile erosion (Fig. 6), measured in two toroidal cross-sections separated by 126 degrees, occurs almost in opposite phase. This is consistent with the disintegration being the result of an m=1/n=1 mode structure, as expected. The reason for the current channel narrowing and its transition into the major disruption could be the cooling of the periphery by impurities, which penetrate into the plasma column during the minor disruption. Sometimes it occurs as a result of LM development after a minor disruption [3]. In the latter case the analogy between TFTR and NSTX would appear practically complete. The essential distinction between them is, however, in the speed of the $T_e(r)$ erosion in the 2nd thermal quench. The characteristic fast thermal quench duration in NSTX appears similar to or longer than that in TFTR and in similar tokamaks.

We measured this parameter in NSTX using the SXR signal. It is obvious that such a method is not quite correct and could give an error on the scale of 2-3. However, in NBI shots the electron thermal quench time during the major IRE almost coincides with the time of a neutron emission drop. The waveforms for such a shot are given in a Fig. 7. The neutron flux (NF) and SXR signal behavior are in general similar. During the minor IRE these waveforms can be different. However, the decay times of electron energy (SXR) and neutron quenches during major IRE's are equal. This is shown in Fig. 8, where the SXR and NF quench times for 17 shots are presented. On the basis of this similarity it is possible to conclude, that the fast ions and hot electrons leave the plasma center simultaneously, i.e. by a convective process. We can assume that the same fast convective transport mechanism is present in a major IRE in NSTX as it is in a disruption in a moderate aspect ratio tokamak. This convective transport mechanism is like the Kadomtsev-Pogutse vacuum bubble [7]. If the thermal quench is the result of a convective mechanism of plasma losses, we are not mistaken in relating the plasma cooling time to the fall of the SXR-signal. The fast thermal quench times (2nd quench) for some tokamaks are given in a Fig. 9 (ITER Physic Basis [8]) as a function of minor radius. We added to Fig. 9 the NSTX data for major IRE's as triangles and for minor IRE's as stars. The local plasma cooling during the minor IRE in NSTX has the same time scale as the fast thermal quench in conventional tokamaks. But the plasma cooling in the major IRE can be almost ten times slower. What plasma parameters does this process depend on?

We analyzed about 50 cases with major IRE's. It was found that this time increases with n_e and has a strange dependence on $q_{95,}$ the safety factor near the plasma boundary. In Fig. 10 the thermal quench time (τ_{tq}) is given for moderate and high n_e. The lower values of τ_{tq} drop to the typical values of conventional tokamaks.

What is the reason for the observable "resonance" at q_{95}=5? Today it is difficult to answer this question. It is possible to suppose, that a tokamak with small A will be more stable to disruptions because it has relatively higher q(a) and dq/dr near the boundary. It could explain the weak influence of minor IRE's on the macroscopic behavior of the whole plasma column. However in analyzed cases of major IRE's the q_{95} is close to q(a) in ordinary tokamaks. In this case the appearance of a current quench is understandable, but it is not clear why the thermal quench duration is more then 5-10 times slower than in ordinary tokamaks. A possible reason could be in the different resonance conditions between the edge and central MHD perturbations for low A tokamaks. As it was possible to see in Fig. 3b, c, d the internal perturbation m=1/n=1 (even expanding outside) can be stabilized for a long time by the hot external plasma in the minor IRE with q_{95}=10. The boundary - center resonance usually destroys this stabilization and leads to a disruption [3]. Possibly the observable "resonance" (Fig. 10) really means an "antiresonance", and the real resonance which destabilized the plasma column is the resonance between harmonics m=4/n=2 (q=2) inside and m=4/n=1 (q=4) near plasma boundary, or correspondingly the m=6/n=2 (q=3) and m=6/n=1 (q=6). The external perturbation m=5/n=1 (q_{95}=5) has no resonance inside the column as serious as the modes m=2/n=1 or m=3/n=1 with their harmonics. Thus, it is possible to simply understand this strange "resonance" in Fig. 10. Unfortunately the behavior of impurities, important for understanding the process of minor and major IRE, is outside of our analysis.

The impurity penetration into the plasma center during the disruption is the key process leading to the current quench in tokamaks. Fig. 11 [4] shows an example of impurity behavior in two minor and major disruptions in T-11M. The impurity (Li) radiation was observed *tangentially* near the torus axis by a narrow (0,2 a) vertical array of AUXV channels (Fig.11), which act as a set of fast bolometers with 2 μsec time resolution. The source of Li was the limiter, located in the bottom of the figure. In the conditions of the experiment the Li atoms, which entered the plasma, would radiate strongly for about 100-200 μsec before complete ionization. Its first ionization is finished after several μsec and the main source of Li I was the light Li-ions. Fig. 11 shows the penetration of Li ions into plasma as deep as 0.5a (center of the column was between channels 1-3) in both minor disruptions for the time 50-100 μsec. The rapid penetration of Li into the plasma center as a result of an internal disruption leads to the major disruption. It is obvious that such fast movement of Li ions across the plasma column can be explained only as convective movement from the boundary to the center of a plasma column. It is possible to suppose that both convective movement out and in plasma center during disruption have one origin. In this situation the impurity penetration to the center should also be suppressed in tokamaks with small A. Probably, this quality - the protection of the plasma center against impurity penetration - makes them more stable relative to the current quench development, i.e. to major disruption.

CONCLUSIONS

1. The NSTX data analysis shows that the sequence of events of minor and major IRE's in NSTX is essentially similar to that for disruptions in moderate aspect ratio tokamaks.
2. The main feature of disruption dynamics in NSTX apparently affected by small aspect ratio appears in the relatively slow thermal quench event (5-10 times longer compared to ordinary tokamaks), which precedes the major IRE.
3. The coincidence of the electron and neutron quench times during the major IRE leads us to the conclusion that the fast ions and hot electrons leave the center of a plasma column simultaneously, i.e. convectively, which is complicated in NSTX, probably by low A.
4. Impurities, penetrating into the plasma center during the disruption play an important role in the current quench and disruption dynamics. It is possible to expect, that in small aspect ratio conditions, when delta-q between the center and the plasma boundary should be higher than in ordinary tokamaks, the convective transport of impurities during the disruption will be complicated too. It may be that this reason explains the enhanced stability of small aspect ratio tokamaks to major disruptions, and that could be the subject of future investigations.

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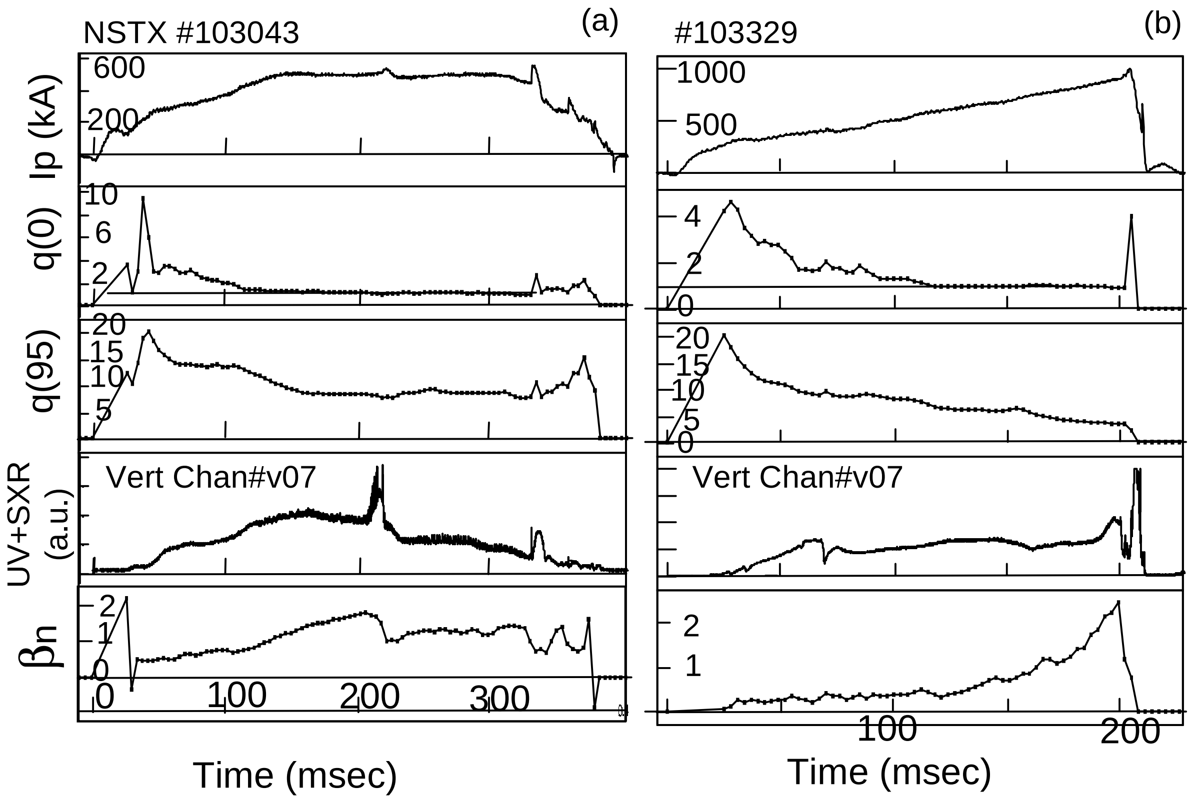

Fig.1. The main NSTX parameters (plasma current I_p, q(0), q_{95}, UV+SXR, and β_n) as a function of time in minor (a) and major (b) IRE

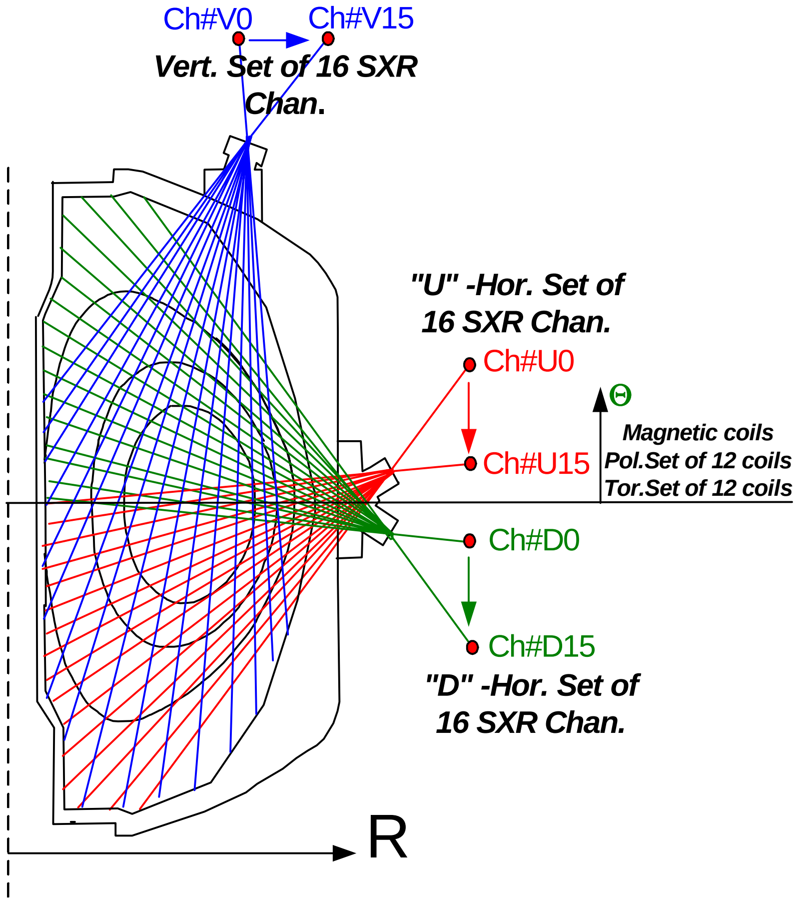

Fig. 2. Diagnostic geometry [5].

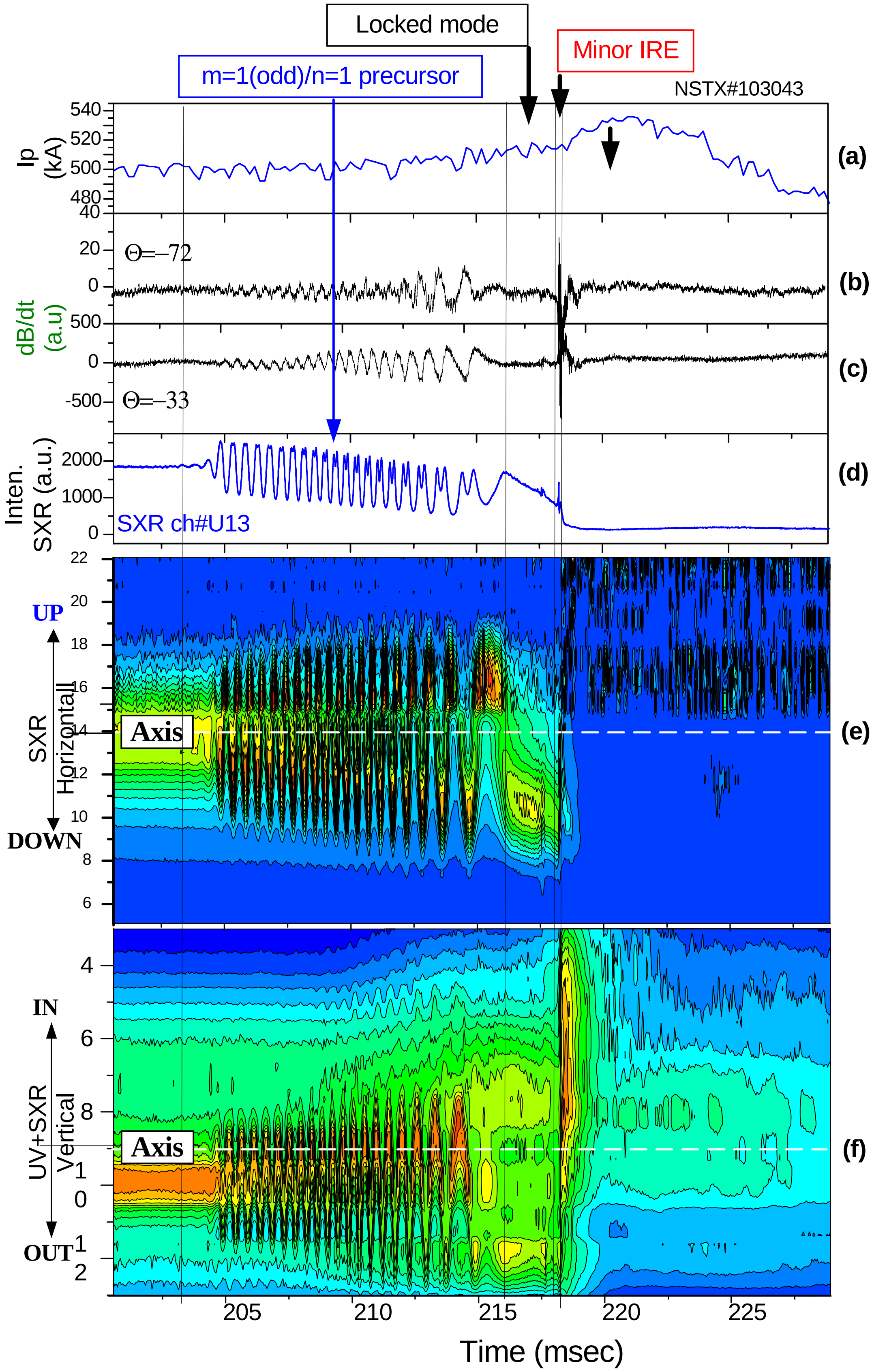

Fig3. The minor IRE (#103043): (a) – plasma current I_p, (b) - dB_θ/dt signals at $\varphi = 72^0$, (c)- dB_θ/dt signals at $\varphi = 33^0$, (d)—SXR-signal from plasma, channel #13 (close to plasma center), (e) and (f) – SXR- mapping for horizontal and vertical arrays.

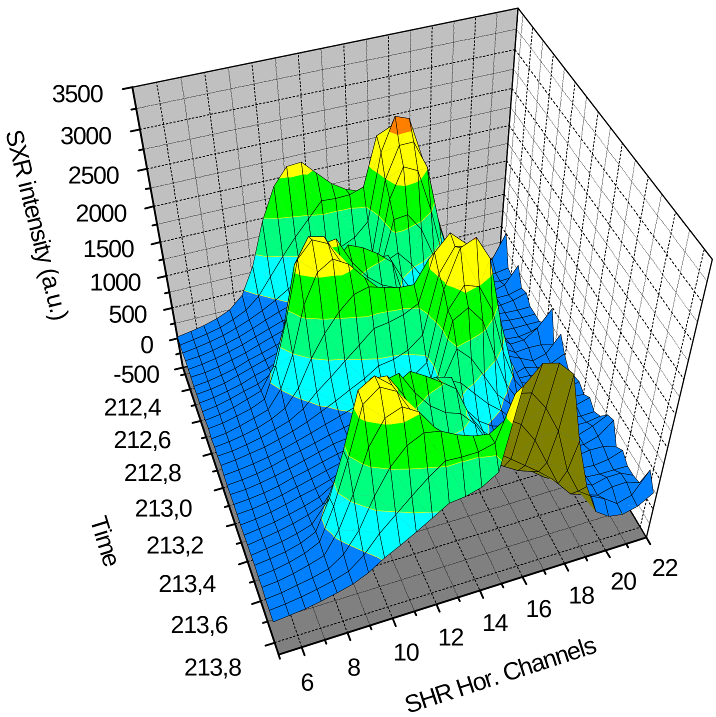

Fig.4. The geometry of SXR-perturbations in minor IRE (#103043).

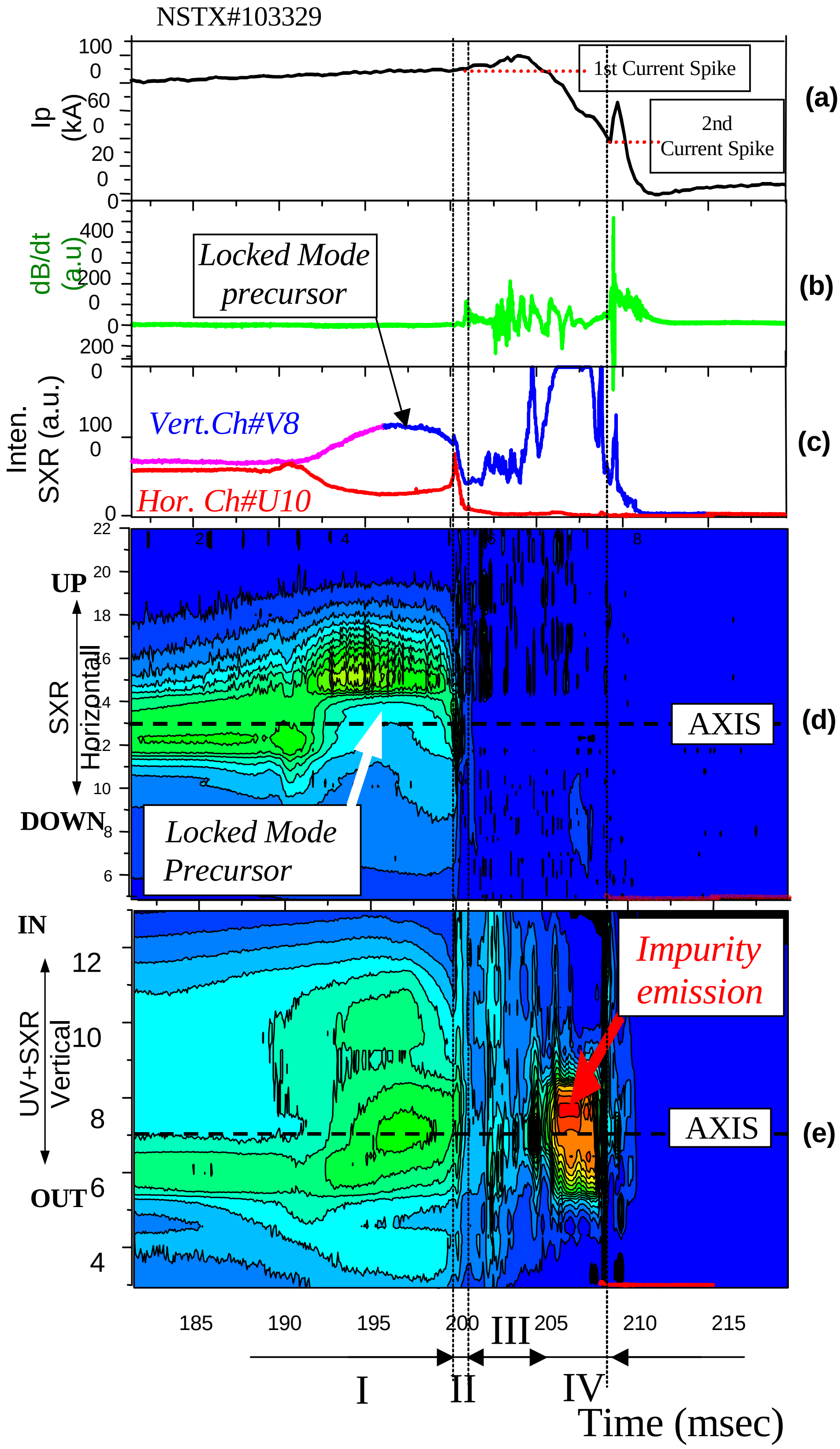

Fig.5. Phenomena sequence in major IRE (#103329), (a)- plasma current I_p, (b)- magnetic probe signal dB_θ/dt, (c)- vertical (UV+SXR) and horizontal SXR signals, (d) and (e) – SXR and UV+SXR mapping.

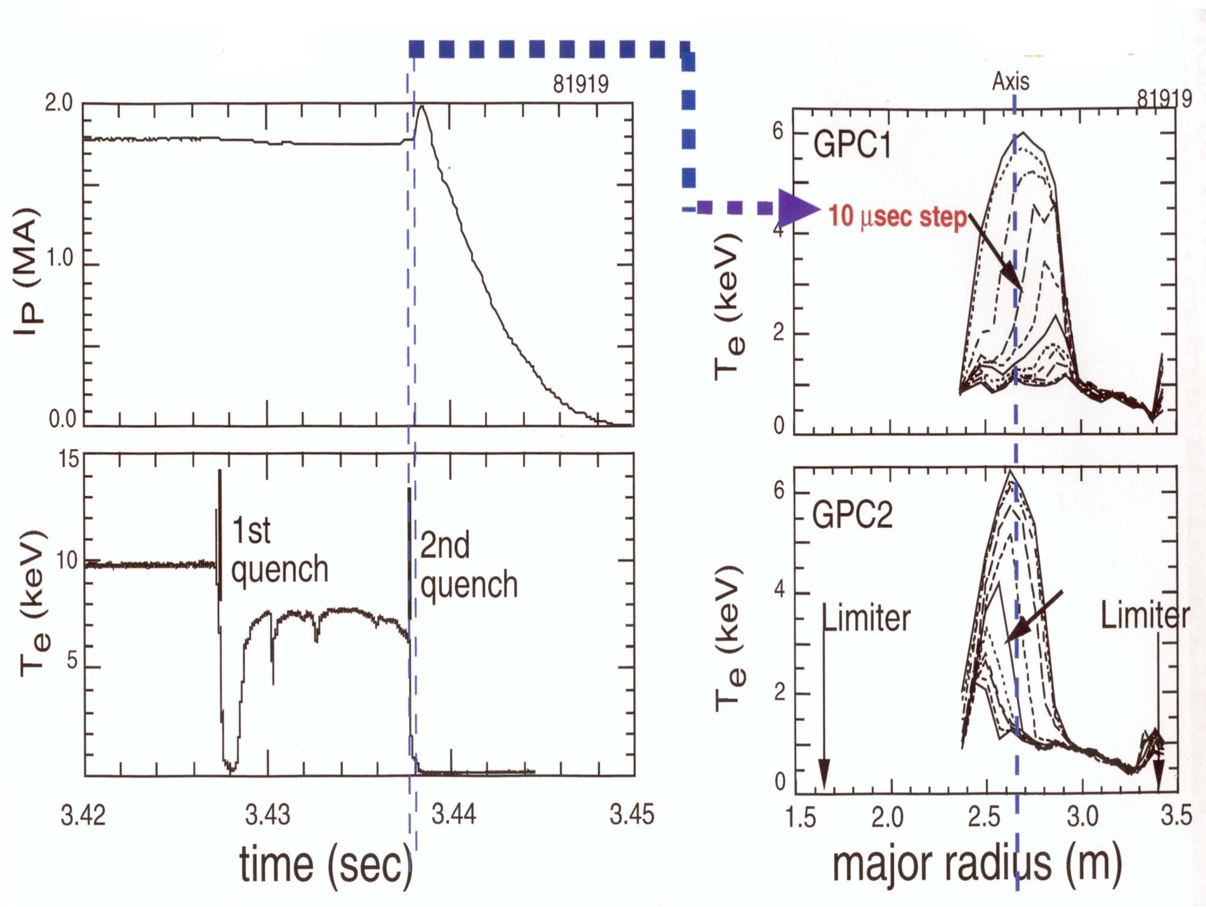

Fig. 6. Dynamics of the major disruption in TFTR [2].
Cold Kadomtsev - Pogutse bubble during fast thermal quench.

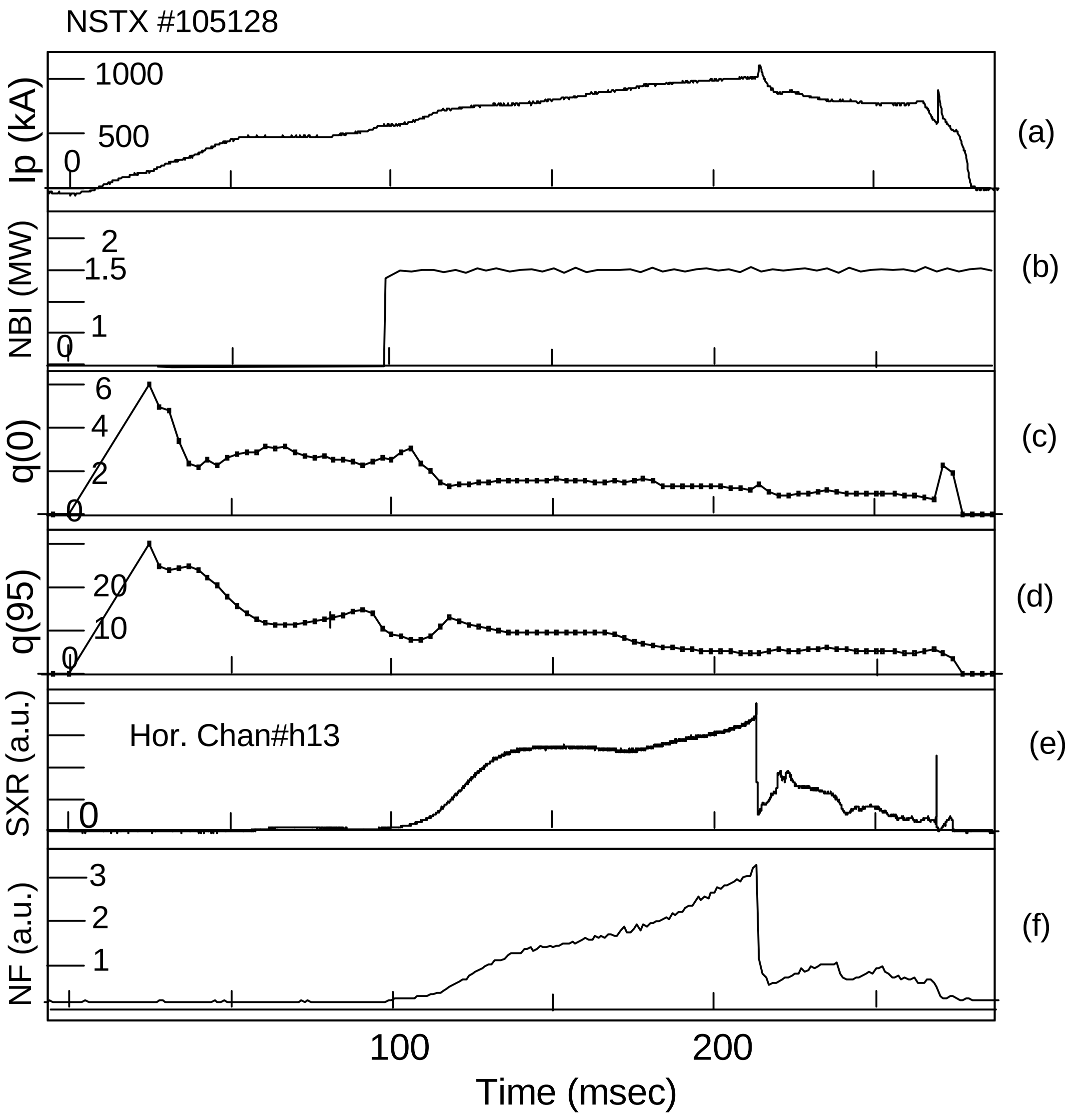

Fig. 7. Time behavior of the main plasma parameters during major IRE in NSTX with NBI-heating: (a) - $I_p(t)$, (b) - NBI power, (c) - q(0), (d) - q_{95}, (e) - SXR and (f) - neutron flux -NF.

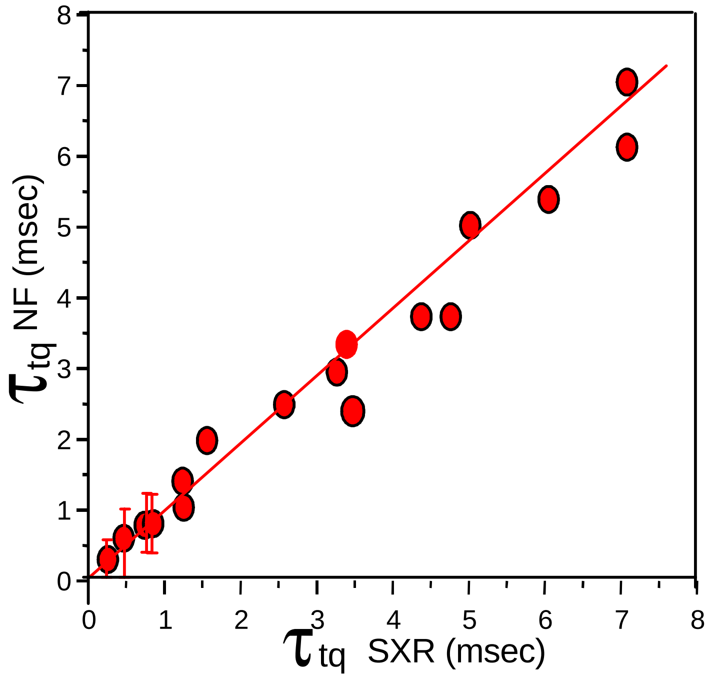

Fig. 8. Neutron and SXR fast thermal quenches. τ_{tqNF} via τ_{tqSX} .

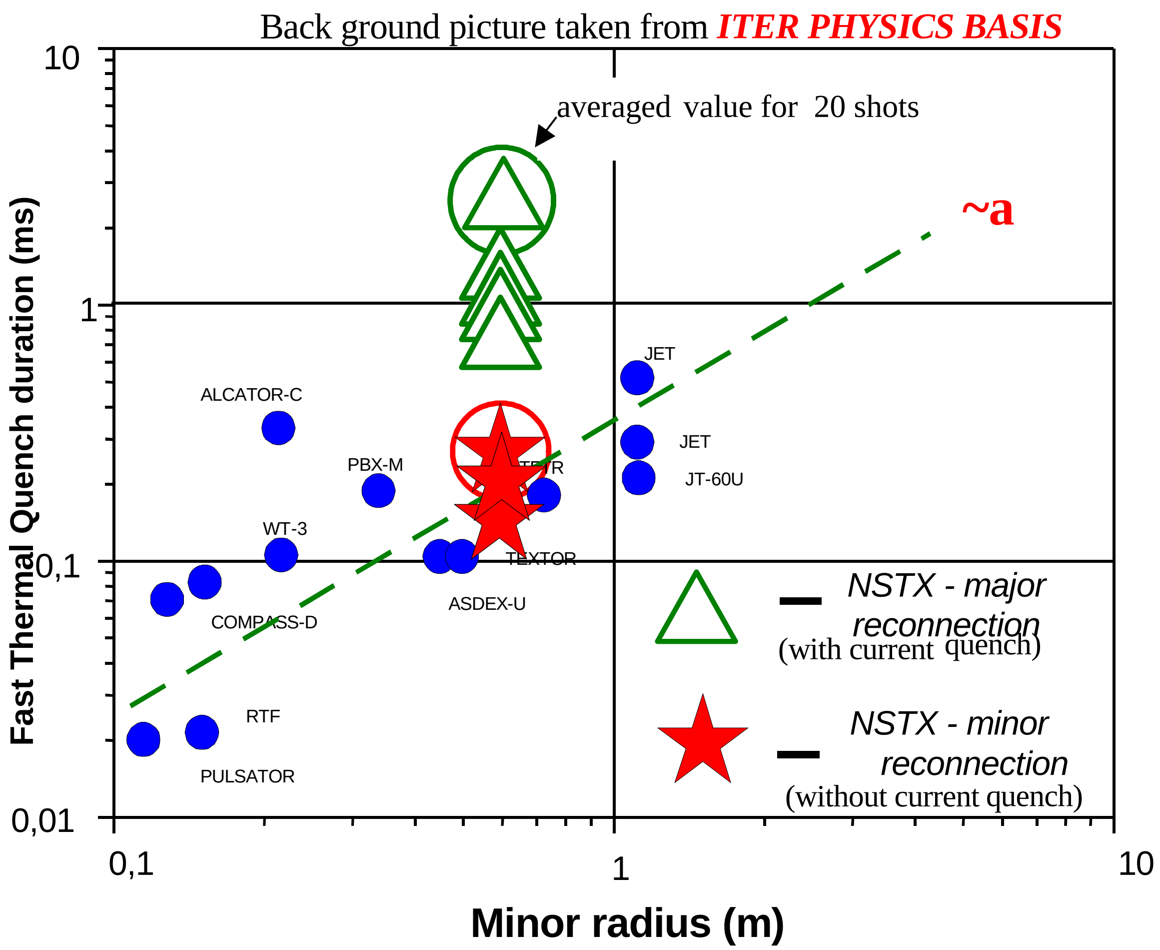

Fig. 9. The fast thermal quench times τ_{tq} for several tokamaks [8] and measured τ_{tqSX} for minor and major IRE.

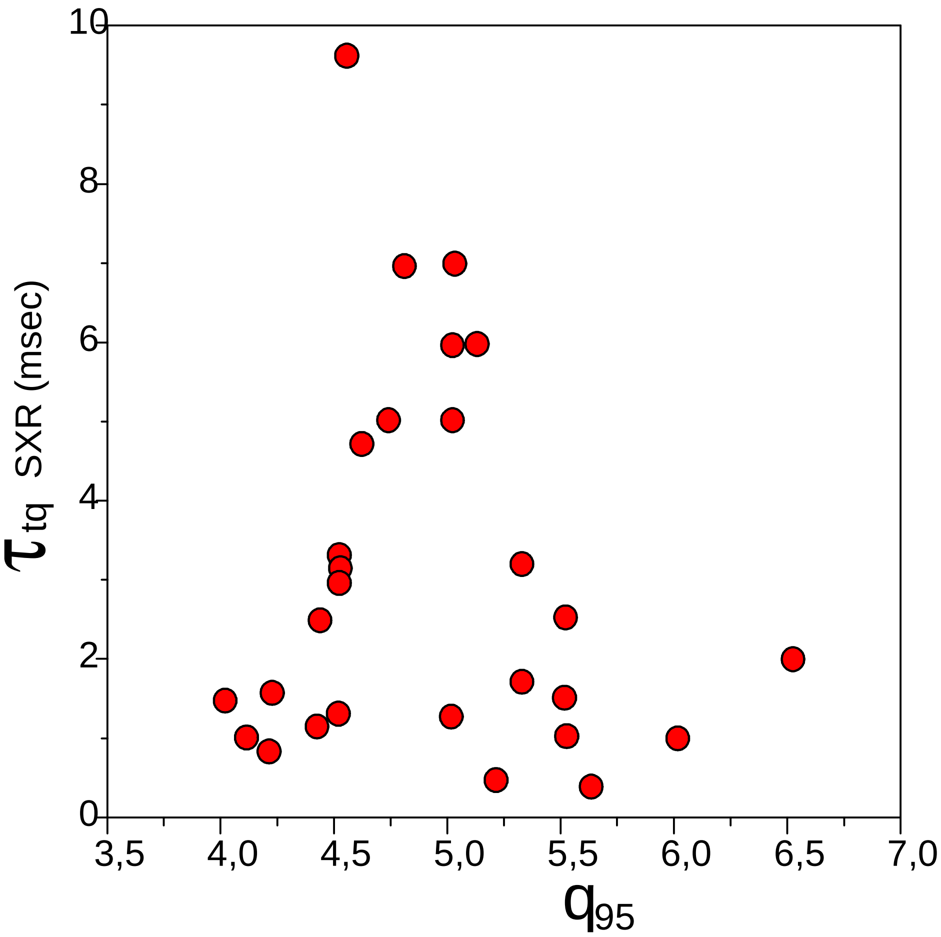

Fig. 10. τ_{tqSX} via q_{95} for several NSTX discharges with high and moderate n_e .

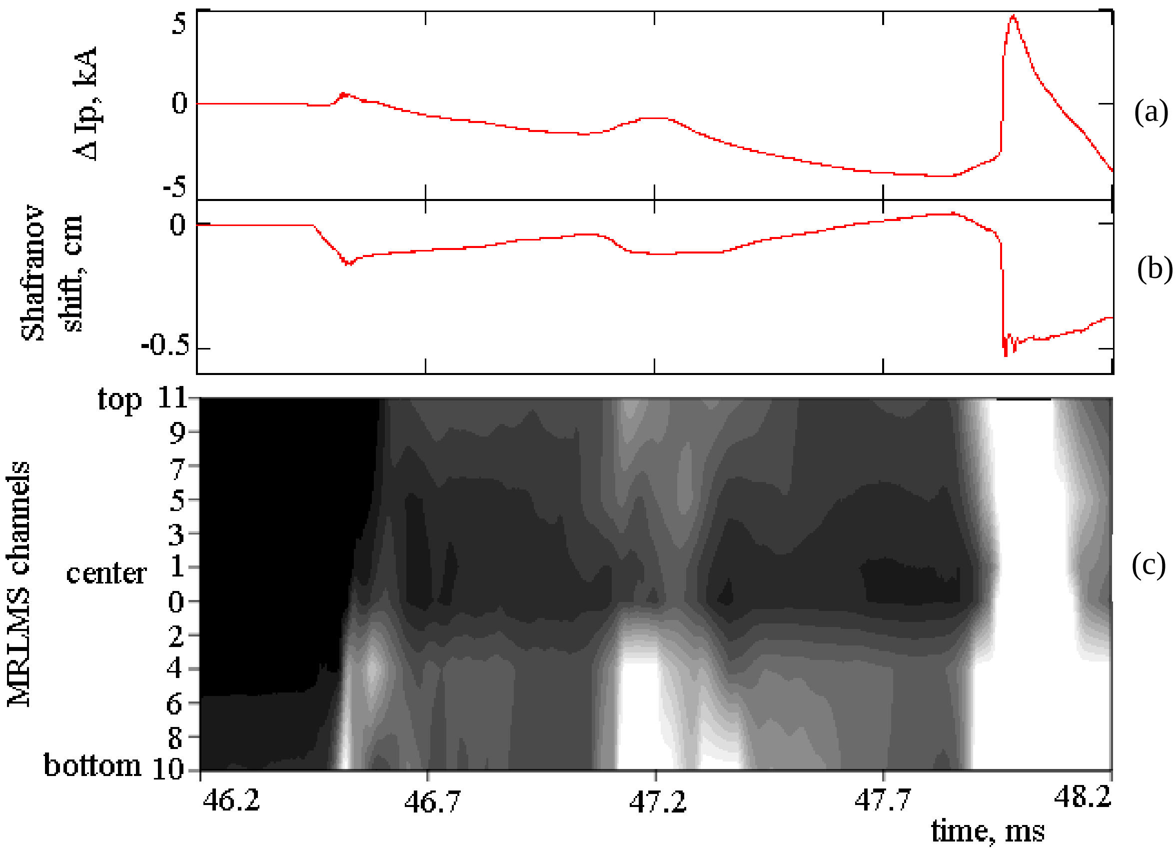

Fig. 11. Fast Impurity (Li) penetration in plasma column during minor and major disruptions in T-11M[4], (a) - ΔI_p – fast part of main plasma current I_p = 80kA, (b) – Shafranov shift, (c) – tangential Li - light radiation (plasma center is between 1and 3 channels).

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