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SAWTOOTH PHENOMENA IN TOKAMAKS

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Abstract

A review of experimental and theoretical investigations of sawtooth phenomena in tokamaks is presented. Different types of sawtooth oscillations, scaling laws and methods of internal disruption stabilization are described. Theoretical models of the sawtooth instability are discussed.

1. Fundamental properties and classification of sawtooth oscillations

The sawtooth collapse is a characteristic feature of tokamak operations. For the first time it was observed in tokamaks ST [1,2], TFR [3], T-4 [4,5] as the oscillations of soft-X-ray radiation intensity (I_{sxr}). The recurrent sharp flattening of I_{sxr} profile was found to be followed by smooth recovering of its initial form. As was shown lately, this process is associated with flattening of radial distribution of electron temperature T_e and density n_e . This fact brings out the drastic enhancement of heat and particle transport during collapse. It was established that sawtoothing results in oscillations of many other plasma parameters.

A great variety of sawtooth collapse evolutions in numerous experiments manifests itself in different spatial-time structures and amplitudes of periodic plasma perturbations.

1.1. Normal Sawtooth oscillations

In the first tokamak experiments (ST [1], TFR [3], T-4 [6]) an axisymmetric rearrangement of I_{sxr} profile, having m=0, n=0 structure, was found to emerge during sawtooth collapse. The characteristic time of I_{sxr} profile reformation in the process of internal disruption is δt=10-100 μs. I_{sxr} reduction in the central plasma region is accompanied with its growth out of a certain surface, I_{sxr} being constant (in the first approximation) at this surface. The presence of such a surface is a characteristic feature of the internal disruption instability development. This surface is known as the surface of sawtooth oscillations phase inversion, and its radial co-ordinate as inversion radius.

In experiments [1,3,6] it was also recognized that relatively slow growth of sinusoidal oscillations, caused (by authors opinion) by rotation of kink m=1, n=1 perturbation with growth rate $\gamma \cong 2\text{-}3\ 10^3\ s^{-1}$ [1], precedes the development of axisymmetric m=0, n=0 perturbation.

Lately these results were extended by TFR experimental data [7,8]. It was shown, that axisymmetric (m=0, n=0) I_{sxr} profile redistribution begins from the $r=r_s$ surface and after this seizes all the plasma center. In these experiments the discussed profile redistribution was associated with m=1, n=1 oscillations amplitude reaching a certain value (that is, with magnetic island localized near the surface of sawtooth oscillations phase inversion and reaching a critical width).

The described sawtooth collapse development is a characteristic of small tokamak experiments and of JET and TFTR operations with low q, q_L < 4-6, (q_L is the safety factor at the plasma boundary) when instability zone is not large. The sawtooth oscillations, corresponding to this process, are known as "simple" or "normal". Such regimes are characterized by relatively small skin times ($t_{sk} \cong 0.1$ s for small tokamaks and $t_{sk} \cong 1$ s for TFTR [9]). According to calculations, peaked radial current density j(r) distribution and monotonic q(r) profile with q(r=0)<1 realize in the plasma under these conditions. This is confirmed by poloidal magnetic field measurements by the Faraday rotation of the radiation polarization plane [10].

1.2. Sawtooth oscillations in large tokamaks. Rapid collapse

In contrast to axisymmetric development of the plasma perturbation during sawtooth collapse in small tokamaks, in large tokamak JET the shift of central plasma region (region with maximal radiation intensity) and formation of kink configuration, having m=1, n=1 structure, emerges[11-12]. (Characteristic central zone velocity $V_{shift} \cong 2 \ 10^3$m/s.) Simultaneously I_{sxr} decreases because of poloidal run of the shifted hot region. The principle difference of these experiments from the small tokamaks is the absence of precursor m=1, n=1 oscillations. At the same time kink m=1, n=1 structure formation takes place during the sawtooth crash. Sometimes kink m=1, n=1 perturbation retains after sawtooth collapse (successor). The characteristic decrement of this perturbation is $\gamma \cong 0.1\text{-}0.5 \ 10^3 s^{-1}$.

Short collapse time (rapid collapse) is also a characteristic of JET internal disruptions, $\delta t \cong 100$ μs [12,13]. This time is essentially less than that calculated in accordance with Kadomtsev model [14]. Such a sawtooth collapse instability development is typical for the high temperature and large size plasma experiments (large skin times : $t_{sk} \cong 3\text{-}4$ s). These sawtooth collapse characteristics are supposed to be due to flattened parallel current profile in large tokamaks [15,16].

1.3. Double sawtooth oscillations

Giant (or double and compound) sawtooth oscillations are similar to that discussed above. Such oscillations are observed in tokamaks: JET - in low $q_L < 6$ regimes [13], DIII-D - during neutral beam injection and in $q_L < 2$ regimes [17,18], TEXT - during current reincreasing [19], TFTR - in $q_L < 4$ regimes [20]. The term "giant" results from the fact that the oscillation amplitudes of different plasma parameters are significantly larger than those in the normal sawtooth process. (In particular relative modulation of T_e increases up to 2 compared to 1.1 - 1.2 during normal sawtooth). Perturbations, enveloped all central plasma region (full mixing of plasma parameters during sawtooth collapse), are typical for these sawtooth oscillations. However, according to experiments, plasma perturbations develop sometimes in a ring region, $r_{in} < r < r_{out}$, and don't affect central region [13,17-20]. Such sawtooth oscillations are known as "partial" or "subordinate". They exhibit themselves irregularly in time in between the big sawtooth oscillations in the low $q_L=2$ regimes and also during ramp up phase. As the calculations point out, skined $j(r)$ profile distribution (non-monotonic $q(r)$ profile with two resonant surfaces) can be realized in plasma under these conditions.

1.4. Sawtooth oscillation structure under auxillary heating conditions

The influence of auxiliary heating on the development of internal disruptions greatly depends on T_e and $j(r)$ profiles. The most distinctly it can be seen in ECRH experiments, when additional power contribution is relatively local ($r_*<r_L$, r_* being the half-width of absorbed in plasma power profile) [21-26]. When electron cyclotron resonance zone is just over the surface of sawtooth oscillations phase inversion, flattening of T_e profile near the $r=r_s$ surface takes place and internal disruptions stabilization is observed. If additional power is absorbed at the surface of sawtooth oscillations phase inversion, T_e profile peaks in the central plasma region and flattens near $r=r_s$ surface. Under these conditions sufficient enhacements of sawtooth periods and amplitudes are observed ($T_{s,ECRH}/T_{s,OH}\cong 2$, $[\Delta T_e/T_e(0)]_{ECRH}/[\Delta T_e/T_e(0)]_{OH}\cong 5$). Auxiliary power absorbtion just inside $r=r_s$ surface results in relative T_e profile peaking in $r=r_s$ region and sawtooth oscillations period decreasing ($T_{s,ECRH}/T_{s,OH}\cong 0.5$). Sawtooth oscillations amplitudes increase with this ($[\Delta T_e/T_e(0)]_{ECRH}/[\Delta T_e/T_e(0)]_{OH}\cong 2$) [26].

The radius of sawtooth oscillations phase inversion doesn't change under these additional heating conditions, and also during ICRH and NBI in JET [27] and TFR [28]. This may be connected both with relatively small times of auxillary heating ($t_{add}<t_{sk}$) and with I(r) shape conservation.

In the experiments on tokamaks JET, TFTR, JT-60, under condition that input power is as large as possible for the present time, the characteristics of internal disruptions development depend on a number of factors: plasma configuration and composition, power level, type of IC antenna [28,29]. It is, apparently associated with the different profiles of absorbed power. The sawtooth oscillations amplitude enhancement is a characteristic for all such experiments [28,29]: $\Delta T_e / T_e(0) \cong 30-50\%$ (15% OH); $\Delta T_i / T_i(0) \cong 10-15\%$ (5% OH).

In a number of cases additional heating results not only in the sawtooth oscillations amplitude growth, but in change of internal disruption development features. Thus on DIII-D tokamak, appearance of double internal disruptions is observed when neutral beam is injected into plasma. Such double disruptions are associated with skin current density profiles [18]. Nevertheless, in JET experiments spatial-time structure of plasma perturbations under additional heating conditions doesn't differ from one observed in regimes with Ohmic heating [11].

2. Theoretical models of internal disruption instability development

In spite of the presence of a wide set of experimental data, the problem still remains unclear: whether the realization of this or that mechanism of the plasma perturbation development in the act of internal disruption is a result of changes in the plasma conditions or that in geometry of experiments and in the application of various methods of treatment. However, a characteristic feature of almost all the experiments is the correspondence between the internal disruption and m=1, n=1 mode development proceeding it or manifesting directly in the very act of internal disruption. The development of such a perturbation is related with the existence of the region with $q(r)<1$ in the plasma. Indeed, even in the first experiments on ST-tokamak [1] it has been shown that a surface of phase inversion in sawtooth oscillations ($r=r_s$) coincides with the position of the q=1 surface, calculated from the experimental radial electron temperature and effective plasma charge distributions, assuming the Spitzer plasma conductivity. This result was later confirmed by many experiments (see, e.g., [30,31]).

The dependence between the internal disruption development and the presence of the plasma region with $q(0)<1$ was also confirmed by the current density profile measurements on TEXTOR [10], ASDEX [32], JET [33].

The presence of the surface with q=1 and the correspondence between the internal disruption and m=1, n=1 mode allows one to assume that the development of such perturbation is the cause for the internal disruption. However, as shown by experiments on TFR [3,34], PLT [35], Pulsator I [36], TEXT [37], the presence of such a perturbation in the plasma is not a sufficient condition for the internal disruption development. Dependent on the plasma conditions (at various q_L , n_e , T_e etc), the m=1, n=1 oscillations can be absent before the internal disruption, meanwhile in other cases the internal disruption is a weak modulation of sinusoidal oscillations m=1, n=1 (see, e.g., [9]). This is also confirmed by the low hybrid current drive experiment, where the internal disruption stabilization is observed under independent development of m=1, n=1 oscillations.

In spite of the mentioned circumstances, practically all the modern theoretical models impose a dependence between the emergence of internal disruption and the development of an internal kink mode. In [38] it has been shown that if the resonance surface q=1 is within a cylindrical plasma, the ideal kink m=1 mode turns out to be always unstable. In connection with this, it has been considered that the sawtooth oscillations are provided by an ideal instability and emerge each time, when the condition q=1 in the plasma is satisfied. This conclusion, however, is invalid for the toroidal geometry. The analysis, made in [39,40] has shown that the presence of resonance surface q=1 inside the plasma is not a sufficient condition for emergence of an ideal kink (mode) instability. This instability emerges only when the parameter β_p, characterizing the ratio of plasma pressure, exceeds some critical value, β_p^{cr} ($\beta_p^{cr} \cong 0.2-0.3$) (precise value of β_p^{cr} essentially depends on the longitudinal current density profile configuration). According to the experiments [15], the internal disruption can emerge at β_p within the range much lower than the instability threshold for ideal mode determined in [39,40]. In this case, the characteristic times of the disruption process turn out to be too short to be explained by the development of a resistive (not ideal) instability [11,13].

A theory relying on the resistive modes for explaining the internal disruption process comes across the problem that, according to the analysis made in the approximation of a cylindrical geometry, these modes have no stability threshold [42,43].

2.1. Resistive kink modes

The models, considering the resistive kink instability as a cause of the internal disruption, suppose that monotonic q profiles with q(0)<1 realize in tokamaks [39,40]. Corresponding profiles were observed in experiments [33,44,45]. As has been pointed out, for such q(r) profiles ideal kink mode is stable for low plasma pressures, and the aim of the theory is to define resistive m=1 mode stability boundary. Taking into account the toroidal effects, one may deduce that the local flattening of q profile near the resonant surface (that is decreasing of |q'(r)|) reduces the resistive perturbation growth rate. When the condition $\gamma=\gamma_R$, where γ_R is the inverse skin time, is satisfied, one may consider resistive mode to be stable and treat this condition as stability boundary. The conclusion, that resistive modes are stabilized when q'⇒0 is in agreement with experiment [44], where stable against internal disruption q(r) profiles with q(0)<1 were observed. Nevertheless, a number of experimental characteristics of internal disruption development can't be explained in the framework of the model considered:

a) Characteristic times of the internal disruption development in large tokamaks are often sufficiently shorter than those predicted by the theory [51].

b) Times of evolution of T_e and n_e profiles during the sawtooth collapse are different [52].

c) Variation of q profile during the sawtooth collapse in tokamaks TEXTOR [10] and JET [33] is small. The q value doesn't exceed than unity under this conditions.

d) Unambiguous connection between development of m=1, n=1 perturbation and internal disruption is absent (see, e.g., [35]). An abrupt variation (to 100 times) of magnetic island m=1, n=1 growth rate during sawtooth collapse emerges [7,8].

2.2. Models treating non-monotonic parallel current profiles

In the case of skinned current profiles two [53] or more [18] resonant q=1 surfaces may realize in a plasma. Non-monotonic q profiles with two resonant surfaces were studied firstly in [53]. Such profiles were not observed in the experiments, but numerical simulations favoured their existence in tokamaks [18,54,55]. In this case magnetic lines reconnection process may take place in a ring region, where $q(r)<1$. (For this reason double sawtooth oscillations appearance is considered to be explained by non-monotonic q profiles.) After reconnection initial axisymmetrical configuration restores with the outer magnetic island (island that was formed in the beginning of reconnection at the outer resonant surface) placed in the plasma center. The inner magnetic island comes to mixing zone boundary.The q value doesn't exceed than unity after sawtooth collapse. Magnetic lines reconnection can proceed without capturing central plasma region under these conditions.

Numerical modulations describe self-consistently experimental $T_s(n_e)$ functions [56] and also the influence of EC heating on the sawtooth collapse development in T-10 tokamak plasma in low $q_L=2$ regimes. Calculations, carried out on the base of this model, permit to describe so-called compound disruptions, observed in large tokamak experiments [18]. However, this model can't explain the contradictions, which are characteristic of resistive mode model in tokamaks with monotonic q profiles.

Theoretical analysis of ideal m=1 kink mode stability shows [57-59] that in tokamaks with two resonant surfaces this mode is unstable even in zero pressure limit. Moreover, the ideal instability exists when the resonant surface is absent at all, provided that the value of $(q(r)_{min}-1)$ doesn't exceed some critical value [58,60]. Nonlinear stage of the ideal kink instability in tokamaks with non-monotonic q profiles without resonant surfaces was investigated in [61]. Close nonlinear equilibrium was found in this paper. In [62] this equilibrium was shown to be unstable against ballooning modes. In connection with this two-step mechanism was suggested: ideal kink instability resulting in nonlinear equilibrium, and ballooning instability resulting in disruption.

2.3. The Wesson model (flattened q-profiles)

In [15] the model was suggested which supposes that a region with highly flattened q profile exists in a tokamak plasma. Hypothesis of [15] is called by the necessity to explain low sawtooth collapse instability thresholds against plasma pressure, and also by the divergence of Kadomtsev model [14] with experimental data. The model [15] is confirmed by experimental q profile measurements [10,32,33,63-65] and by numerical simulations [66,67]. Indirect experiment data also support the suggestion [15]. These are: quasi-interchange plasma displacement [11] and snake-like oscillations [68] (see also [69].

Because of the circumstances pointed above attention is drawn to numerical [16,70-72] and analytical [73-76] investigations of internal kink modes in tokamaks with flattened q profiles. Analysis which has been carried out in these papers, indicates decreasing of β_p^{cr} with q profile flattening increasing. Profiles with $q(0)>1$ are the most unstable, growth rates maximum achieving at some finite $q_{min}>1$ value.

Wesson himself pointed out the drawbacks of his model [16]. The ideal instability growth rates should be of order of inverse collapse time for this instability to explain internal disruption. According to experimental data, such an increment should arise when q(0) change is very small ($\delta q \cong 10^{-5}$). But it follows from the theory, that only the changes $\delta q \cong 10^{-3}$ can result in growth rates required.

3. Influence of internal disruption instability on tokamak plasma parameters

The role of sawtooth oscillations in tokamak operating exhibits the most distinctly in low $q_L \cong 2$ regimes and in regimes with auxiliary heating. So, on JET tokamak sawtooth modulation amplitude of electron temperature T_o in plasma center reaches 50% in auxiliary heating regimes with $q_L \cong 2$ [51]. Such a large T_o modulation in thermonuclear reactors may result in sufficient reduction of thermonuclear power density output. This will complicate the achievement of stable reactor operation. Sawtooth oscillations amplitudes of plasma parameters increase with decreasing q_L is a characteristic for many tokamak experiments (Table 4).

With low q, sawtooth collapse influence spreads on entire plasma column. This fact is supported by MHD activity outbursts and surface voltage flashes, correlated with sawtooth collapse, which were observed in many tokamak experiments [20,51,77]. In these regimes poloidal magnetic field perturbation near the plasma boundary is as great as $\delta B_p \cong 10^{4}$ T, and level of high frequency oscillations (15 kH) of poloidal magnetic field increases up to two times [78]. Plasma perturbation in the central region during sawtooth collapse results in development of small scale plasma oscillations [79-81] and in electron heat transport coefficients increasing (from 2 to 40 times) in entire plasma column (increasing the heat transport from central plasma region [9,82]). With this the most enhance (to 10-100 times) of turbulence level (level of plasma density fluctuations with frequencies 0.1-0.2 MH ($k_\perp \cong 7$-24 cm^{-1})) during sawtooth collapse is observed in the central plasma region [80].

In high q_L regimes ($q_L > 3$-4), when the sawtooth oscillations amplitude is relatively small, heat losses, caused by internal disruption instability, make 10 to 15% of total losses from plasma central zone. In low q_L regimes, $q_L < 3$, when sawtooth oscillations amplitude is large, auxiliary heat losses in the central plasma zone reaches 15% to 50% [83-85]. However, even under these conditions the contribution of internal disruption to total energy losses doesn't exceed several percents. Significant influence of internal disruption on plasma energy confinement is observed only in a few experiments on DIII-D and PBX tokamaks in low q and high β ($q_L \cong 2$-3, $\beta_p \cong 2$-3%) regimes. With this, sharp decreasing of total plasma energy supply emerges in the act of internal disruption. Under these conditions the development of large amplitude sawtooth oscillations in some cases results in major disruption and prevents large β achievement [86].

In the experiment on DIII-D tokamak an essential effect of internal disruption on the particle transport process in the central plasma region has been shown [87]. In those experiments operating with low q_L ($q_L \cong 2$), a reduction (four times) in Ni ion density at the plasma column center (flattening of n_{Ni} profile) is observed in the development of internal disruption. It has been related with a steep enhancement in the diffusion across the magnetic field in the act of internal disruption. Indeed, in the experiments on Alcator-C [88] and PLT [35] it has been shown that the injected impurity profile flattening (Si and Al) occurs directly in the act of internal disruption. It can be explained by a high (10^4 times) increase in the diffusion coefficient in the central plasma column region ($r<r_s$) in the act of internal disruption [35].

Maximal amplitudes of oscillations in various plasma parameters are given in Table 1.

4. Scaling laws

The measurements of sawtooth oscillations periods attract widespread attention. The characteristic repetition times (sawtooth oscillations period, T_s) are essentially different under different operating conditions (from 1ms on ST [1] to 1s on JET [89]). However, similar dependencies of T_s on the discharge parameters (I_p , B_T , n_e , r_L etc) have been obtained on many machines. A rise in T_s with increase in the plasma density at the plasma column center, $n_e(0)$, or in the plasma density averaged over the volume, $\bar{n}_c$, is especially characteristic. Similar dependences are also typical for the plasma energy confinement time, t_E, characterizing the times of $T_e(r)$ and $T_i(r)$ profile rearrangements, [90,91]. Indeed, in the experiments on TFTR [20] and JET [92] a correlation between T_s and t_E has been revealed: $T_s \cong (0.13 \pm 30\%) t_E$ [92], $T_s \cong 0.2 t_E$ [20]. This can show that the period of sawtooth oscillations is determined by a characteristic profile rearrangement time, $T_c(r)$, and hence, by $j(r)$. The dependence between the period of sawtooth oscillations and other discharge parameters is less definite. It is possible that it is related with various ranges of parametric changes in various experiments. The experimental scaling laws for the period of sawtooth oscillations are given in Table 2.1.

An analysis of experimental sawtooth oscillations period dependences on plasma parameters and the study of energy balance in the central plasma region show that a slow ($t>t_{crash}$) peaking of the $T_e(r)$ profiles in a time interval between successive internal disruptions can be explained by Ohmic plasma heating

[31]. The T_e profile peaking corresponds to that of j(r) and q(r) profiles. The start-up of internal disruption is determined in various models from the conditions q(0)=1 [93] or $q(r_1)=1$ at a non-monotonic profile of q(r) [94]. In other models the period of sawtooth oscillations is determined from the condition of achieving a critical island width m=1, n=1 ($W_{1,1}=r_s$ [95] or $W_{1,1}=2r_s$ [31]). In this case, the m=1, n=1 islands growth is assumed to occur with a rise in the shear (S=(r/q)/(dq/dr)) in the central plasma column zone due to a peaking in the j(r) profile in between successive internal disruptions. Theoretical scaling laws for sawtooth oscillations are given in Table 2.2.

The scalings laws for the radius of inversion (Table 3) and for the amplitude of sawtooth oscillations (Table 4) are of interest, along with the sawtooth oscillation period scaling laws.

5. Internal disruption stabilization, relationship with a current density profile modification

5.1. Internal disruption suppression in the development of magnetic field perturbations

A strong effect of internal disruption on the characteristics of a central plasma column zone (see Table 1) makes the search for technique of internal disruption stabilization to be urgent. Even in 1978-1979, in the experiments on Pulsator [96] and TOSCA [97], an possibility to suppress the internal disruptions by creation of stationary magnetic field perturbation having the structure m=1,n=1, was demonstrated. For this purpose some stationary helical coils allowing one to produce additional perturbations in the magnetic field within the surface q=1 were used. This results in the emergence of a zone with enhanced transport in the region of this surface that can, in its turn, provide the current j(r) density profile flattening [97]. The complete disappearance of sawtooth oscillations was observed when the width of this zone (interpreted in the paper as a new magnetic island m=1, n=1) is of the order of the sawtooth phase inversion radius.

Later in the experiments on tokamaks HT-68 [98], T-7 [99] it has been shown that the imposition of a stationary magnetic field development with m=2 at a rather high amplitude produced by external helical coils can produce the internal disruption stabilization. An effect of sawtooth oscillation stabilization is also observed under spontaneous development of the kink m=2, n=1 instability of rather high amplitude, $\Delta B/B \cong 0.5-1\%$ [6,99-102]. It can be related with the j(r) profile flattening in the central zone due to the m=2, n=1 perturbation effect or due to dynamic stabilization of the m=1 and m=2 harmonics in the toroidal plasma column [103].

Probably the internal disruption stabilization under development of "soft" mode - stationary helical plasma perturbation ($\Delta B_p/B_p \cong 4\ 10^{-3}$) observed on T-10 under operation conditions with low $n_e \cong (1.5-2.5)10^{19} m^{-3}$ [104] - occurs due to these mechanisms.

5.2. Internal disruption stabilization under ECRH

The first experiments on the internal disruption stabilization under ECRH were done on T-10 in 1983 [21]. The main results of these experiments have later been confirmed on CLEO [22], PDX [23], DIII-D [24], TFR [25]. A possibility to stabilize the internal disruption in a wide range of discharge parameters has been shown. The internal disruption suppression is observed, when the ECR zone is located beyond the sawtooth oscillations phase inversion surface and near it. For the complete stabilization of internal disruption the ECH power, $P_{microwawe}$, should be not less than the power of Ohmic heating P_{OH} ($P_{microwawe}/P_{OH}$>1 to 5). Stabilization of internal disruptions is related with the $T_e(r)$ profile flattening in the sawtooth phase inversion surface zone [21]. In this case, as calculations show, a change in the j(r) profile does not exceed a few percent and the value q(0) does not exceed than unity. It is necessary to note that, in difference from experiments on JET [89], under these conditions suppression is probably not related with kinetic effects. This is confirmed by the fact of retaining the Maxwellian electron velocity distribution under these conditions.

5.3. Internal disruption stabilization under an effect of low-hybrid waves

The suppression of internal disruption under an effect of low-hybrid waves, found in the experiments on tokamaks PLT [105], Petula-1 [106], ASDEX [107], Alcator-C [108], is observed in the operation, when the current is driven by a beam of supratherma,l high energy electrons. The complete stabilization of internal disruption is observed at a rather high power of lower-hybrid waves, $P_{LH}>P_{OH}$. Stabilization of internal disruption in these experiments is related with the j(r) profile flattening due to generation of run-away electrons. It is confirmed by a reductions in the central plasma discharge inductance [105-107] and by Zeeman splitting of Li ion line from the j(r) profile measurements results [32]. In this case, however, the quantity q(0) probably does not exceed than unity. That is confirmed by the absence of supression of *m*=1, *n*=1 oscillations, assosiated with the presence of q=1 surface in the plasma. The localization zone of these oscillations does not change under low-hybrid wave pumping.

5.4. Internal disruption stabilization under ICRH and under NBI

The longest time of internal disruption stabilization (Δt up to 3.2 s) has been achieved in the present-day experiments on JET and TFTR [89,109] under NBI and (or) ICRH at the plasma column center. Internal disruption stabilization under these conditions is related with the generation of accelerated ions with the energy up to E ≅2 Mev. The internal disruption by which a stable state is terminated has a high amplitude. In this connection, the phenomenon under discussion is called "monster sawtooth".

The role of the j(r) profile change under these conditions is not quite clear. Calculations of the j(r) profile, according to the data on electromagnetic measurements, show that the safety factor at the plasma column center, q(0), under these conditions is reduced by 5-10% (q(0)≅0.9-1.0) [89]. It is confirmed by the results of measuring the poloidal magnetic field by the Faraday rotation of a polarization plane in the exploring radiation which also reveal a reduction in q(0) under internal disruption stabilization [33]. However, the internal plasma column inductance is practically not changed in these experiments that speaks about a weak change in the j(r) profile [89].

Generation of a bootstrap current [89] is a characteristic feature of operating conditions under auxiliary high power heating on large tokamaks JET and TFTR. As shown in calculations, up to 90% of this current should pass outside the sawtooth oscillations phase inversion surface. It can result in flattening of the j(r) profile in the vicinity to the q=1 surface. In this case, however, the quantity q(0) does not exceed unity, since the absolute value of the auxiliary bootstrap current is not great ($I_b/I_p \cong 10\%$ [89]).

6. Conclusions

An analysis of experimental features in the development of internal disruption within the plasmas in various tokamaks and the comparison between these features and theoretical models allows one to make the following conclusions:

1. A strong effect of internal disruption on the plasma parameters in the central plasma region is manifested under operation conditions with low $q_L \cong 2-3$ and with high β_p only.

2. There are no unambiguous dependence of sawtooth parameters (growth rate, period, amplitude, localization zone) on integral plasma parameters (I_p, B_T, r_L etc). The period of sawtooth oscillations is related with characteristic times of electron temperature profile rearrangement.

3. Plasma perturbations in the act of internal disruption have the structure m=1, n=1 and m=0, n=0. A spatial-time structure of plasma perturbations in the act of internal disruption depends on the $T_e(r)$ profile shape (or q(r)) in the central plasma column zone. There is a correspondence between the m=1, n=1 mode development and an internal disruption, however an unambiguous dependence is absent.

4. The internal disruption development under operating conditions with low q_L (at the flattening of the j(r) distribution) is in agreement with the internal ideal m=1, n=1 mode development theory. Under operating condition with high q_L (at the peaked j(r) distribution) characteristic features of internal disruption can be represented within the framework of the internal, resistive m=1, n=1 mode development models

5. Internal disruption stabilization occurs under local flattening of the current density profile in the vicinity of the q=1 surface.

6. The presence of a zone, where q(r)<1, in the plasma is not a sufficient condition for the internal disruption development. At the same time, the theory shows that the internal disruption development will also be possible in the absence of a resonance surface in the plasma too, if the value q_{min} is rather close to unity (flattened and non-monotonic q profiles).

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Table 1

Maximum Sawtooth Amplitude

parameter	amplitude	regime	facility	ref.
$T_e(0)$	20%	OH	JET	[51]
	50%	ICRH	JET	[51]
$T_i(0)$	50%	ICRH	JET	[51]
$n_e(0)$	30%	OH	Tuman3	[110]
$I_{neutron}$	30%	OH	TFTR	[20]
β_p	12%	ICRH+NI	JET	[51]
	7%	NI	PBX	[86]
U_{sur}	25%	OH	TFTR	[20]
P_{rad}	10%	OH	TFTR	[20]
b_{pol}	0.01%	ICRH	JET	[78]
b_{pol}^{15kHz}	100%	ICRH	JET	[78]
J_{5360A}	0.5%	OH	Alcator-C	[111]
$V_{tor.rot.}(Ni^{27})$	40%	NI	JET	[112]

$T_e(0)$, $T_i(0)$ - electron and ion temperatures,

$n_e(0)$- electron density,

I_{neut}- neutron flux,

$\beta_p=8\pi n_e(T_e+T_i)/B_p^2$,

b_{pol}- poloidal magnetic field fluctuations ($2<m<6$),

b_{pol}^{15kHz}- magnetic field turbulence (15kHz),

J_{5360A}- light radiation intensity (λ=5360A),

$V_{tor.rot.}$-ion toroidal rotation velocity (Ni^{27}),

U_{sur} - surface voltage.

Table 2.1

Experimental Sawtooth Period Scalings

facility	scaling	ref.
JET	$n_e(0)^{0.4}\ B_T^{-0.9}\ T_e^{1.3}\ Z_{eff}^{-0.7}$	[113]
TFTR	$n_e(0)^{0.6}\ R_0\ r^{1.4}\ U_{sur}^{-0.15}$	[114]
TEXT	$n_e(0)\ I_p^{-1}$	[37]
TFR	$n_e(0)\ R_0^2\ B_T^{-1}\ I_p$	[115]
T-10	complex dependence on plasma parameters	[26]
FT	$\langle n_e\rangle^{0.5}$	[116]
Puls I	$n_e(0)$	[117]
DIVA	$\langle n_e\rangle$	[118]

R_0 - large tokamak radius,

B_T - toroidal magnetic field,

I_p - full plasma current.

Table 2.2

Theoretical Sawtooth Period Scalings

authors	scaling	ref.
MCGUIRE-ROBINSON	$T_{saw}=\tau_R^{3/7}\tau_{Hp}^{2/7}\tau_h^{2/7}$	[97]
WARD	$T_{saw}=\tau_R^{1/2}\tau_h^{1/2}$	[94]
ALLADIO	$T_{saw}=\tau_h$	[93]
YAMAZAKI	$T_{saw}=\tau_R^{1/2}\tau_h^{1/2}$	[119]
WADDELL-JAHNS	$T_{saw}=(\tau_R^{3/5}\tau_{Hp}^{2/5}\tau_h^{2/5})(r_s/r_w)^{6/5}*$ $*(T_i/T_e)^{1/5}\ \omega_*^{2/5}$	[31]

$\tau_R=\mu_o r_s^2/\eta$ - skin time,

$\tau_{Hp}=R_o\rho^{1/2}/B_T$ - Alfven time,

$\tau_h=3nT/2\eta j^2$ - energy life time,

$\omega_*=m(dT_e/dr)/er_sB_T$ - drift frequency.

Table 3

Sawtooth Inversion Radius Scalings

facility	scaling		ref.
JET	$q_\psi^{-0.8}\ r_{fit}\ k$		[113]
TFTR	$q_L^{-1}\ r_L$		[121]
JT-60	$q_{eff}^{-1}\ r_L$		[122]
TEXT	$I_p/B_T\ \ (\cong q_L^{-1})$		[37]
T-10	I_p/B_T	complex dependence on r_L	[26]
TFR	$q_L^{-1}\ r_L$		[115]
FT	$q_L^{-1}\ r_L$		[116]
DIVA	$q_L^{-1}\ r_L$		[118]
HL-1	$q_L^{-1}\ r_L$		[120]
JT-60,DIII-D,T11,T10	no $n_e(0)$ or $\langle n_e \rangle$ dependence		[85,122]

$q_L\ = 5r_L^2B_T/R_oI_p$,

$q_{eff} = 2\pi a^2B_T/\mu_oI_pR\ [1+(a/R)^2\{1+1/2(\beta_p+l_i/2)^2\}]$,

$q_{cyl} = 5r_L^2B_T/RI_p\ \ [1+k^2(1+2\delta^2-1.2\delta^3)]/2$,

$q_\psi\ = q_{cyl}[(1.17-0.65\varepsilon)/(1-\varepsilon^2)^2]$,

$k\ \ = b/a$ - ellipticity,

δ - triangularity.

Table 4

Sawtooth Amplitude Scalings

X-Ray Intensity Oscillations

facility	scaling	ref.
TFR	$q_L^{-3/2}$	[115]
DIVA	$q_L^{-3/2}$	[118]
FT	$q_L^{-5/2} n_e^{-1}$	[116]
Puls-I	$n_e(0)$	[117]

Electron Temperature Oscillations

facility	scaling	ref.
T-10	$q_L^{-1/2}$ (OH regime)	[26]
	$q_L^{-3/2}$ (ECHR regime)	[26]

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