ITB-events and their Triggers in T-10 and JT-60U

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Abstract Non-local transport bifurcations inside and around ITB (abrupt variations of transport in a ms timescale within 30-40% of minor radius) were found in various JT-60U reverse shear (RS) and normal shear (NrS) plasmas and called ITB-events. The abrupt reduction of transport in the central part of the plasma column often interrupts a slow diffusive inward cold pulse propagation (CPP) in T-10. CPP is created by a cut-off of the off-axis ECRH. This phenomenon may referred to ITB-events as well. In many cases transport is halved in a wide region $0<r/a<0.3$-0.4, when the central safety factor q decreases below unity. In some cases, ITB-events are also observed during a CPP created by the reduction of ECRH power. In this case sawteeth do not appear in a new steady-state, and the existence of q=1 surface at the time of ITB-event is called in question. In JT-60U low-power-heated RS plasmas, ITB-events are observed at the crossing of q_{min}=3.5,3,2.5 values. Internal MHD n=1 activity has been reported earlier as ITB-events trigger in JT-60U. The present paper shows the new MHD triggers of ITB-events in JT-60U. ITB-event is triggered by a series of small internal disruptions probably associated with q=2.5 surface in RS plasmas. ITB-event occurs in a ms timescale correlation with the start of ELMs series in high-β_p NrS shot. The total heat flux reduces abruptly in the zone $0.3<r/a<0.7$ (by 3 times at the reduction maximum). The calculated radial electric field (with assumed neoclassical poloidal rotation) changes little at the ITB-event. The ms correlation between the start of ELMs series and the reduction of the heat flux gives possibility to control the ITB formation immediately and non-locally by inducing the ELM-like MHD activity.

1. Introduction

Understanding of the Internal Transport Barrier (ITB) properties and identifying the control method of the ITB are nowadays among the most important issues for tokamak fusion research. The formation ITBs near the rational surfaces of the safety factor q=2,3 in normal shear (NrS) or optimized shear discharges of JT-60U and JET is well known [1,2]. The interrelation between ITB and Edge Transport Barrier (ETB) is also observed. In JT-60U high triangularity plasmas with type I ELMs, the pedestal β_p and the (normalized) pressure gradient in the ETB were enhanced by an increase in total β_p [3].The transient processes detected under crossing of q minimum q_{min}=3 in reverse shear (RS) plasmas were observed in JT-60U for the first time [4]. Later, non-local confinement bifurcations inside and around ITB (abrupt variations of transport in a ms timescale within 30-40% of minor radius) were found in various JT-60U RS and NrS plasmas and called ITB-events [5-7]. In RS JT-60U plasmas, the role of q_{min} equal to 3.5,3,2.5,2 depends on the level of NBI power [8]. ITB-events are observed at q_{min} = 3.5,3,2.5,2 in shots with low power and at various levels of q_{min} in shots with higher power. A series of ITB-events (after n=1 MHD activity with f=7 kHz) creates a strong ITB in H-mode (q_{min}~2.7) and doubles the energy confinement time [7]. The formation of ITB was preceded by the fishbone activity on the q=2 surface in ASDEX Upgrade RS shots [9]. The influence of the radial electric field near ITB foot on wider ITB region was highlighted in [10]. Initially, another type of non-local (in ~90% of volume) abrupt jumps (bifurcations) of transport at fast "global" L-H-L transitions was detected in JET and JT-60U plasmas with NrS [11,12]. At L-H-L transitions in JT-60U plasmas with RS and weak ITB [6,7], the profile of the electron heat flux jump $\delta\chi_e(r)$ covers wide region up to $0.3<r/a<1$ including the ITB zone. In T-10, ITB was detected by means of heat pulse propagation (HPP) and cold pulse propagation (CPP) analysis in target sawtooth-free plasma created by off-axis ECRH [13,14]. Moreover, the reduction of central q value during CPP sometimes leads to interruption of diffusive CPP process by an abrupt decrease of transport in the central region [14].

2. ITB-events in the central part of T-10 plasmas with suppressed sawteeth oscillations

The aim of the present section is to show the transport phenomenon, which occurs during the inward CPP. The target sawtooth-free plasmas were created by off-axis ECRH. Figure 1(a) represents T_e behavior during CPP created by off-axis ECRH cut-off in shot 35762 (I_p/B_T =0.18MA/2.34T, resonance at r/a=-0.45). CPP with χ_e^{CP} ≈0.3 m^2/s inside r/a < 0.3 occurs in a 15 ms time interval (see [13] for detail on the numerical method). The value of R/L_{Te} at r/a=0.27 rises up to 11 in comparison with the value equal to 7 during Ohmic heating (OH) phase. Later, the reduction of the heat transport interrupts diffusive CPP. Figure 1(a) shows the reduction of the heat transport at t=0.638s. Probably, we can call this phenomenon ITB-event (or central ITB-event). Typically, ITB-events appear 10-20 ms before the first crash when q=1 surface does not exist (or q=1 at r=0 within the errorbars of calculations); however, a wide zone of low shear (below 0.1) exists in the central part of plasma column. In this shot, the profile of the electron heat flux jump $\delta\chi_e(r)$ at ITB-event covers a wide region 0<r/a<0.35 and transport reduces approximately twice at r/a=0.15-0.25. Abrupt decrease of the heat transport was observed regularly in ~50 shots under various plasma parameters obtained over several past years. Roughly speaking, 3 types of ITB-events can be recognized depending on the appearance of sawteeth oscillations. The q=1 surface plays an important role in the cases when ITB-events occur straight before the first sawtooth oscillation and, probably, when ITB-events occurs 10-20 ms before the first sawtooth crash (see figure 1(a)).

ITB-events are also observed after reduction of ECRH power, when sawteeth oscillations do not appear in a new steady state. Figure 1(b) displays the reduction of the transport at the time shown by a vertical line. In this case, the absence of sawteeh oscillations means that q=1 surface does not exist in accordance with the Kadomtsev model. The existence of q<1 region is a necessary but not sufficient condition for sawtooth crashes in many tokamaks (e.g. see [15] for T-10 plasmas). Some other models of sawtooth

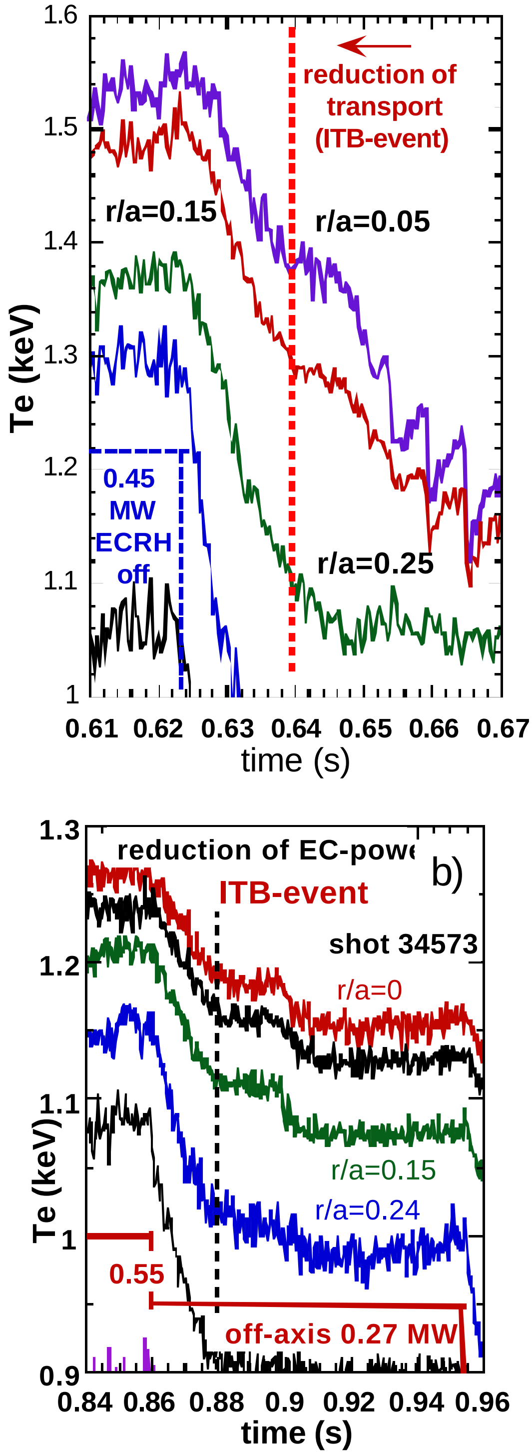

Figure 1. *(a) Interruption of diffusive inward CPP created by off-axis ECRH cut-off. Abrupt decrease of transport in a central zone is observed as disappearance or deceleration of the decay at time shown by a second vertical line. (b) Similar reduction of transport after a partial reduction of ECRH with new sawtooth-free steady-state*

crash allow the existence of q=1 surface together with low normalized gradient of pressure (see [15] and references therein) . In the shots with the reduced power of the off-axis ECRH, the pressure gradient is indeed reduced in comparison with the OH level. We can conclude that in some cases ITB-events are caused by the q=1 surface; however, in other cases this is not true, if we assume that Kadomtsev model is valid. Nevertheless we cannot fully ignore the possibility of the q=1 surface existence even in the case when the sawteeth oscillations are absent. Dependence of the central ITB-event (onset condition, $\delta\chi_e(r)$ value etc.) on plasma parameters is not fully understood so far.

3. ITB-events with various triggers in JT-60U

In this section, we first analyze ITB evolution in high-β_p NrS plasmas 1.5MA/3.8T discharge E34487. Time traces of this NBI-heated discharge are shown in figure 2 with the injected NB power P_{NB}, stored energy W_{dia}, H_α, electron temperatures T_e, and ion temperature T_i. The evolution of T_i is given according to the charge-exchange recombination spectroscopy data (17ms time resolution). We can briefly describe the plasma evolution shown in figure 2 as follows. Weak ITB is created before 4.6s. The ITB event I (ITB-Improvement) occurs at t = 4.602s, as marked by the vertical line in figure 2. Two BLM-crashes (BLM; Barrier Localized Mode) occur at t = 5.0 and 5.1s. The second ITB-event D (ITB-Degradation) is observed at t = 5.985s (70 ms after P_{NB} was switched-off) shown by the second vertical line in figure 2. The ITB-event D is observed as a spatially inverse T_e perturbation in comparison with the ITB-event I.

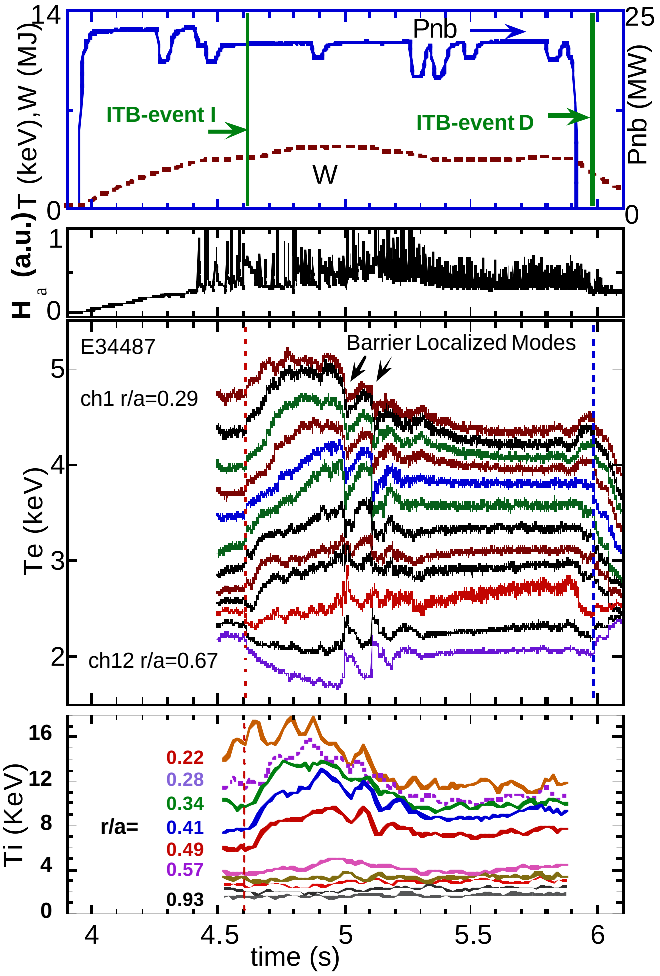

Figure 2 (a-d) Evolutions W, P_{NB}, H_a T_e and T_i for a NrS shot 34487.

Figure 3(a) shows the decay of edge T_i and edge line-averaged density n1 after ITB-event I. Figure 3(b) represents the rise of H_α at ITB-event I and n_e peaks after event-I since nL2/nL1 increases (ratio of line-averaged n_e at r/a=0.2 and 0.9) Confinement time increases almost twice after the end of ELMs series

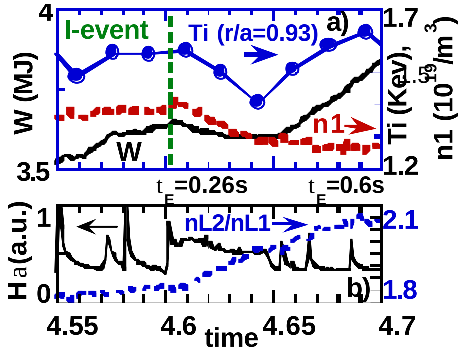

Figure 3. *(a-b) Timetraces of edge T_i, and line-averaged ne1(0.9), W, H_a and ratio of line-averaged ne2(0.2)/ne1(0.9) around ITB-event I shown earlier in figure 2(a-d)*

(from τ_E ~0.26s to τ_E ~0.6s). Figure 4 (a) shows that ITB-event I occurs in a ms timescale correlation with the start of ELMs series that create enhanced level of H_α in high-β_p NrS shot 34487. Time-traces of T_e are shifted closer to each other in order to highlight the ms correlation between the sudden change of dT_e/dt value and the rise of H_α. (brief description was given in our early letter [16]. The variation of ∇T_e is absent in a ms timescale. Calculations of heat flux variation starting from $\delta dT_e/dt$ value (see detail of method in [5-8]) shows the non-local reduction of the electron heat flux in a 0.3<r/a<0.7 region. The absolute value of total electron and ion diffusive heat fluxes reduces by maximum 2.5-3 times. Another similar ITB-event occurs earlier (t=4.49s) and is in the ms correlation with the start of short series of ELMs with enhanced level of H_α. In contrast, ITB-event D (degradation, see figure 2) has no visible trigger besides NBI cut off which occurs 60ms earlier.

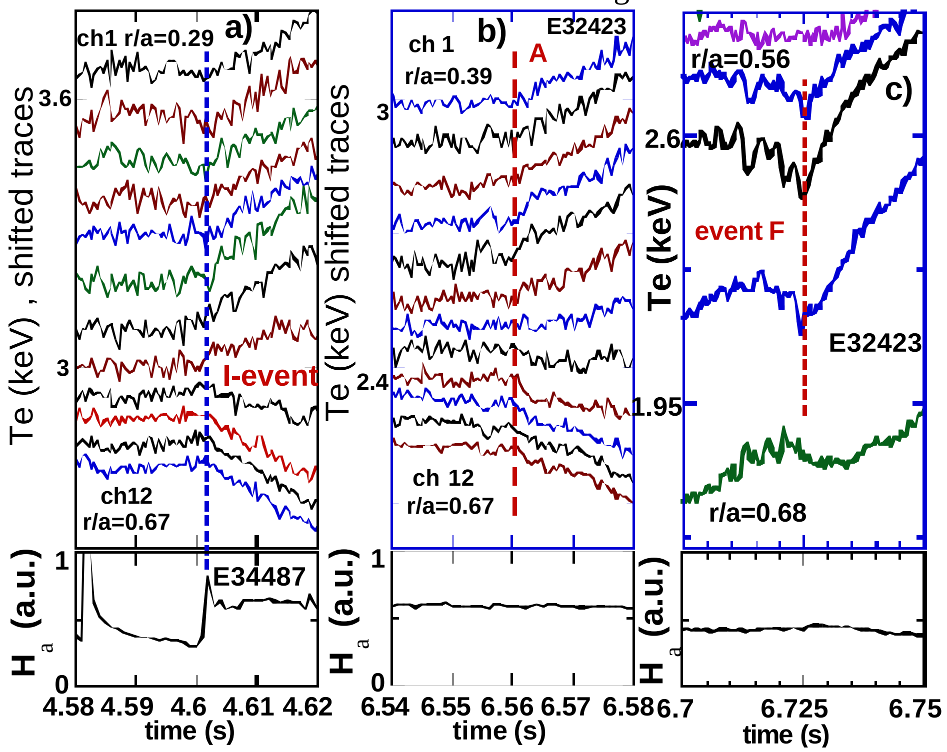

Figure 4. *Timetraces of T_e and H_a around ITB-events in NrS shot 34487 (a) and RS shot 32423(b-c). (a) ITB-event I is triggered by external MHD activity (b) ITB-event A has no obvious trigger. (c) ITB-event F is triggered by internal MHD-activity observed as series of small internal disruptions probably at q=2.5*

Figure 4(b-c) displays new details on the T_e behavior at ITB-events A and F in RS shot 32423 (see the evolution of plasma parameters in [7]). Figure 4(b) highlights abrupt simultaneous change of dT_e/dt values in a ms timescale in the wide region at ITB-event A. ITB-event A occurs without any visible trigger. The absence of visible triggers is typical for numerous ITB-events observed in many of the JT-60U RS shots. ITB-event F is triggered by a series of small internal disruptions probably connected with q=2.5 surface.

The E_r profile is calculated from the profiles of plasma pressure of each species and the measured toroidal rotation velocity of carbon impurity

$$E_r=(dP_i/dr)/(Z_i e n_i) + V_T B_p - V_p B_T. \qquad (1)$$

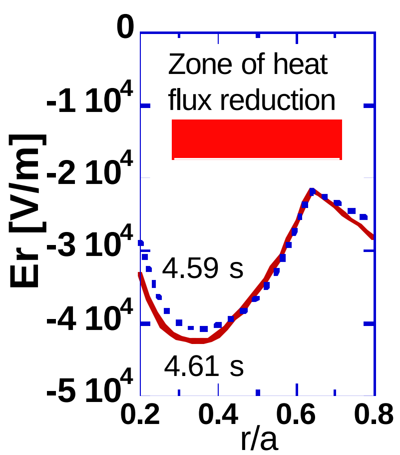

Figure 5. *Calculated E_r does not vary at ITB-event I in figure 2(a)*

Since the poloidal rotation is not measurable at present, it is estimated under the assumption of neoclassical theory. The procedure of E_r profile estimation is described in [17,18]. Figure 5 shows E_r before and after ITB-event I (V_T is measured with 17ms time resolution). E_r changes little at ITB-event I. The variation of E_r is also negligible at ITB-event A. Moreover, the variation of E_r is typically negligible at the times of ITB-events and global L-H-L transitions in various regimes of JT-60U. At ITB-events, the gradient of pressure (see equation (1)) starts to vary in the inversion zone only. It does not vary at all in the wide zone after L-H-L transitions since $T_e(T_i)$ starts to rise simultaneously in the wide zone. V_T starts to vary linearly in some regions only. The abrupt non-local jump of V_T is not observed at ITB-events and L-H (H-L) transitions in JT-60U. Consequently, only the abrupt non-local variation of poloidal rotation V_p can create a non-local variation of E_r. To our up-to-date knowledge, abrupt non-local variation of V_p has not been detected in tokamaks.

4. Cartoon comparison of non-local bifurcations of transport

Now we briefly compare various types of instantaneous edge-core and core-edge interplay and transport bifurcations. In all the cases we consider variations of transport occurred in a ms timescale. Figure 6(a) shows transport variation at the time of global L-H transition in JET and JT-60U [5,6,10-11]. The decay of H_α and the start of edge transport barrier formation cause instantaneous reduction of transport coefficients in the wide zone 0.3 <r/a<1. In RS and NrS shots with ITB, the reduction covers the zone of weak ITB also. Figure 6(b) represents transport variation at the time of global L-H transition in JET [19] triggered by a sawtooth crash. Figure 6(c) displays

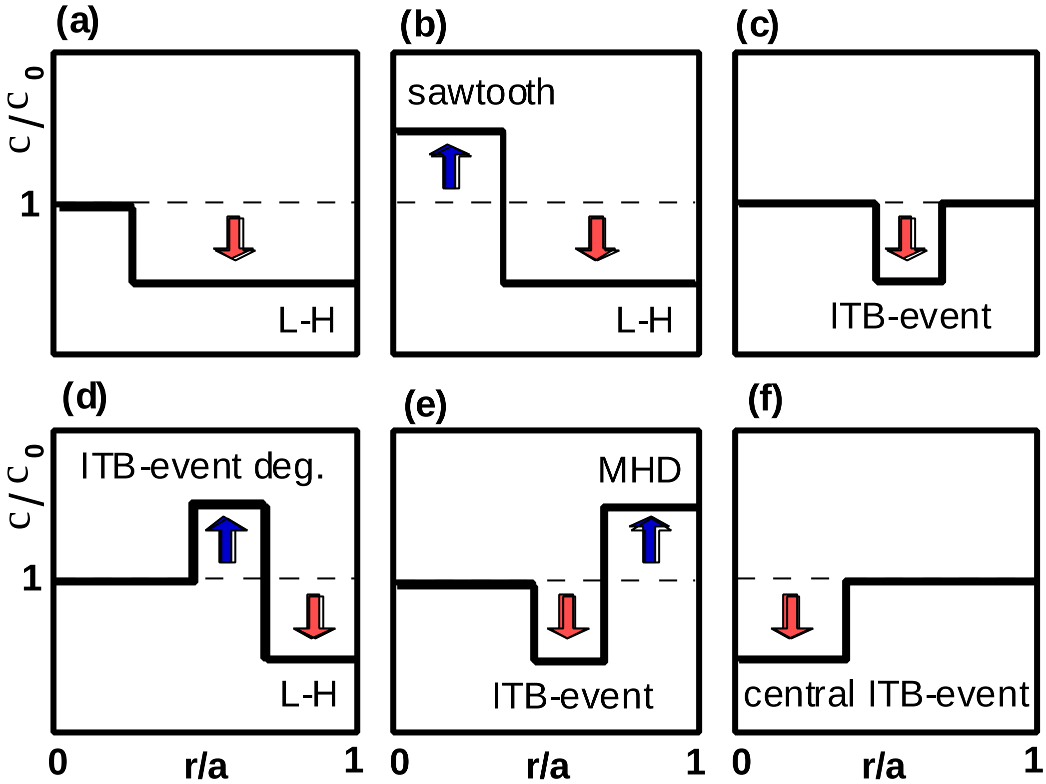

Figure 6. (a-f) Cartoon view of ms timescale variation of the transport at the time of bifurcations (a) Global L-H transition (JET, JT-60U), (b) Global L-H transition induced by sawtooth (JET), (c) ITB-events without trigger and with small internal MHD as the trigger (see figures 4(b,c)) , d) L-H transition triggered by ITB-event degradation, e) ITB-events with external MHD as a trigger (see figure 4(a)), f) central ITB-event at T-10 (see figure 1) and abrupt reduction of transport triggered by evaporation of small C_8H_8 pellet at LHD [20].

ITB-event-improvements without trigger or with small internal MHD activity as a trigger (see figures 4(b-c) and refs [5-8]]). Similarly to sawtooth crash, ITB-event degradation can induce the L-H transition [7]. The scheme of the corresponding transport variation is shown in figure 6(d). Figure 6(e) shows ITB-event with external MHD as the trigger (see figure 4(a)). Figure 6(f) describes the case of central ITB-event at T-10 (see figure 1) and abrupt reduction of transport triggered by evaporation of small C_8H_8 pellet at LHD [20].

4. Discussion and Conclusions

Various cases of core-edge and edge-core interplay are known in tokamaks for many years. The important role of E_r in tokamak plasmas confinement was pointed out in the context of the physical mechanism of L-H transition [21]. The increase of ∇E_r due to hot ion losses at a sawtooth crash was discussed as a reason of L-H transition in JFT-2M [22].
The formation of ITB was preceded by the fishbone activity at the q=2 surface in ASDEX Upgrade RS shots [9]. A possible explanation for fishbones reducing the transport and thus creating an ITB is the interaction between the fishbones and the fast particles arising from NBI injection. The interaction between fishbones and fast particles leads to a redistribution of the resonant non-thermal particles. The resulting current causes a return current in the bulk plasma which gives rise to a sheared plasma rotation which is equivalent to E_r. We speculate that in JT-60U case non-local increase of ∇E_r in reality (not the value calculated using equation (1)) due to losses of fast ions caused by series of ELMs could be responsible for non-local reduction of transport. At the same time, ITB forms definitely in the absence of MHD activity in some ASDEX-U RS discharges [9]. This phenomenon, in our opinion, resembles ITB-events without visible triggers in JT-60U RS discharges. The correlation of the coupled edge-core MHD activity and ITB formation (within ~100ms time interval) was reported in JET [23]. At low magnetic field in LHD, toroidicity induced Alfven eigenmodes (TAEs) transiently induced a significant loss of energetic ions together with the reduction of the transport (with the energy confinement improvement factor 1.3) [24].

In order to understand the non-local property of the transport coefficient, theoretical models have been discussed, either based on the statistical excitation of long-range perturbations (e.g. [25]) or on the spatial spreading of turbulence (e.g. [26,27]). At the same time, it is not always easy to find relationship between turbulence measurements and the transport level. A recent JT-60U paper highlighted that the ion heat transport and the particle transport correlate with the measured density fluctuations, while the electron heat transport seems to be decoupled with the measured density fluctuations [28]. No evidence of the turbulence reduction has been found in LHD at the time of abrupt decrease of the electron heat transport in the core simultaneously with the pellet evaporation at the edge [20]. In T-10, a strong local decrease in the turbulence level and poloidal coherency was clearly seen for radii $0.25 < r/a < 0.35$ after ECRH switch-off [29]. Very low transport coefficients were found in these shots [14]. Moreover, measurements showed that the usual mechanism of turbulence stabilization by $E_r \times B$ shear flows cannot explain the low transport.

The equation (1) shows a negligible variation of E_r after ITB-events (with measured pressure and toroidal rotation velocity V_T). The pressure gradient and V_T do not vary (start of gradual V_T variation) in a short-time scale after global L-H and L-H transitions in JT-60U and JET [12,30]. The applicability of equation (1) to non-local transport bifurcations is called in question. Consequently, it is the abrupt non-local variation of poloidal rotation V_p that can create non-local variation of E_r at the time of ITB-events or global L-H transitions. To our up-to-date knowledge, abrupt non-local variation of V_p has never been detected in tokamaks.
The abrupt reduction of transport in a central part of plasma column often interrupts slow diffusive inward cold pulse propagation (CPP) in T-10. CPP is created by cut-off of the off-axis ECRH. This

phenomenon may be referred to ITB-events as well (low χ_e value and high value of R/L_{Te}). In many cases transport is halved in the wide region 0<r/a<0.3-0.4, which correlates with the appearance of q=1 at r=0 (calculated value). This feature resembles ITB-events in JT-60U low-power-heated RS plasmas [8] where events are observed at crossing of q_{min}=3.5,3,2.5 values. In some cases, ITB-events at T-10 are also observed during CPP created by the reduction of ECRH power. In this case sawteeth do not appear in a new steady-state. However, the absence of sawteeth does not prove the absence of q=1 surface [15].

The present paper describes new MHD triggers of ITB-events in JT-60U. ITB-event is triggered by a series of small internal disruptions probably associated with q=2.5 surface in RS plasmas. ITB-event occurs in a ms timescale correlation with the start of ELMs series that create enhanced level of H_α in high-β_p NrS shot. The total heat flux reduces abruptly in the zone 0.3<r/a<0.7 (by 3 times at the reduction maximum). The calculated radial electric field (under the assumption of neoclassical poloidal rotation) does not vary at ITB-events. The ms correlation between the start of ELMs series and the above-mentioned reduction of the heat flux gives possibility to control the ITB formation immediately and non-locally by inducing the ELM-like MHD activity. New examples of ITB-triggers presented above highlight the importance of further systematical study of ITB triggering with internal and external MHD activity. Successful experiments with repeatable results should bring new knobs for ITER scenario.

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