# Role of Low Order Rational q Values on the ITB-events in JT-60U Plasmas

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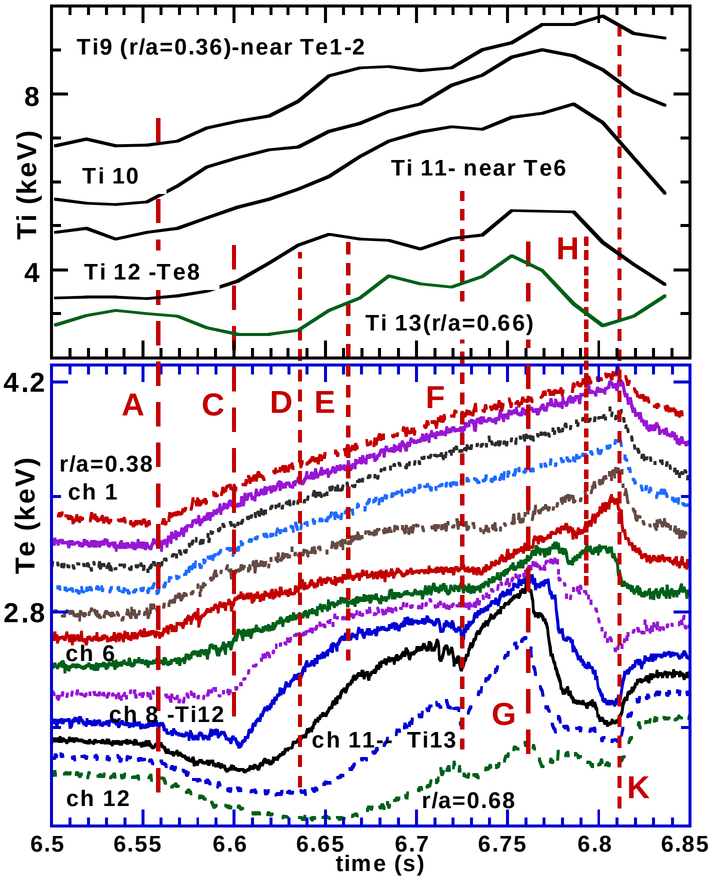
**Abstract.** The formation of internal transport barriers (ITBs) near q=2,3 surfaces in normal (NrS) or optimized shear discharges of JT-60U and JET is well known. In reverse shear (RS) JT-60U plasmas, the role of q minimum ($q_{min}$) equal to 3.5,3,2.5,2 is not obvious for ITB formation. ITB-events (non-local confinement bifurcations inside and around ITB in a ms timescale) are found in various JT-60U NrS and RS plasmas. Under sufficient power, ITB-events are seen at rational and not rational values of $q_{min}$. The space-time evolution of $T_e$ and $T_i$ is similar even being strongly varied in space and time, suggesting same mechanism(s) of $T_e$ and $T_i$ transport. The temporal formation of strong ITB in H-mode under passing of $q_{min}$=3 (after periodical improvements and degradations via ITB-events with 8ms period) in RS mode with $P_{nbi}$=8MW is presented. Under smaller power, ITB-events are observed only at rational values of $q_{min}$. In a weak RS shot with $P_{nbi}$=4MW, abrupt rise of $T_e$ is seen at $q_{min}$=3.5, while more cases of $T_i$ rise are observed. The difference of the $T_e$ and $T_i$ evolution seen regularly under the low power, suggests decoupling of $T_e$ and $T_i$ transport.

## 1. Introduction

The formation of internal transport barriers (ITBs) near q=2,3 surfaces in normal (NrS) or optimized shear discharges of JT-60U and JET is well known [1,2]. In reverse shear (RS) JT-60U plasmas, the role of q minimum ($q_{min}$) equal to 3.5,3,2.5,2 is not obvious for ITB evolution. The transient processes seen under crossing $q_{min}$=3 were first time reported in [3]. Later, non-local confinement bifurcations inside and around ITB (abrupt variations of transport in a ms timescale within ~0.3r/a) were found in various JT-60U RS and NrS plasmas and called ITB-events [4-6]. The maximum of heat flux variation is located near the position of $q_{min}$. The series of ITB-events is able to create the strong ITB in H-mode ($q_{min}$~2.7) with nearly doubled energy confinement time [6]. The influence of the radial electric field calculated near ITB foot on wider ITB region was highlighted in [7]. Initially, another type of non-local (in ~90% of volume) abrupt jumps (bifurcations) of transport at fast "global" L-H-L transitions was found in JET and JT-60U plasmas with NrS [8-9]. At L-H-L transitions in JT-60U plasmas with RS and ITB [5-6], the profile of the heat flux jump follows the position of the safety factor minimum and penetrates into RS region deeper for the weak ITB that for the strong one [6]. ITB-event degradation causes L-H transition [6].

## 2. ITB-events under sufficient NBI power in RS

Under sufficient power in JT-60U RS plasmas, ITB-events are seen at rational and not rational values of $q_{min}$ and the space-time evolution of $T_e$ and $T_i$ is similar [4-6]. In the present paper, we highlight the similarity of $T_e$ and $T_i$ evolution by detailed comparison $T_e$(r,t) and $T_i$(r,t) behavior (see Fig. 1) during strong ITB creation via series of ITB-events-improvements A, C, F and further ITB degradation (shot 32423, 1.5MA/3.7T, L-mode edge, $P_{nbi}$=8MW, $q_{min}$~2.7, see evolution of plasma parameters in [4]). The position and the evolution of $T_e$ measured by 12-channels ECE heterodyne radiometer (data averaged in 0.5ms interval) at channel 11 ($T_{e11}$) correspond to the $T_{i13}$ evolution (changes of timetraces at the times A, D, F, K on Fig.1). The $T_i$ is measured with 17ms time resolution and ~0.06r/a space resolution half width. The $T_{e8-9}$ evolution corresponds to the $T_{i12}$ evolution (changes of slopes at the times C, E, F, H on Fig.1). The $T_{e6}$ position lies near the $T_{i11}$ position (times A, F, K). The $T_{e1}$ position corresponds to the $T_{i10}$ position. The evolution and the similarity of $T_e$ and $T_i$ transport at t=6.5-6.68s time interval was described in detail [4]. The $T_{i,e}$ evolution




presented on Fig.1, shows the similarity of the transport in a longer time interval, including the formation of double ITBs clearly seen before time G (weak ITB between $T_{e2}$ and $T_{e6}$, and strong ITB between $T_{e10}$ and $T_{e12}$. The same trend is observed for $T_i$ profile at t= 6.75s (the difference between $T_{i12}$ and $T_{i13}$ is equal to 1 keV and 2.5 keV for $T_{i13}$ and $T_{i14}$ (r/a=0.73)). Strong ITB destroys after time G.

The timetraces of shot 32474 (1.5MA/3.7T), the evolution of $T_e$ and profiles in H-mode under passing of $q_{min}$=3 are presented on Figs 2(a-d). Four cycles of ITB-events (called periodic ITB-events or P-ITB-events) are seen on $T_e$ evolution after t=6.68s (see Figs 2(c,d). Each cycle consists of ~4ms ITB-event improvement phase ($T_{e3-6}$ rise and $T_{e9-12}$ decay) and ~ 4ms ITB-event

*Fig. 1. Similarity of $T_i$ and $T_e$ evolution in shot 32423. $P_{nbi}$ rises from 8MW to 10 MW at t=6.66 s.*

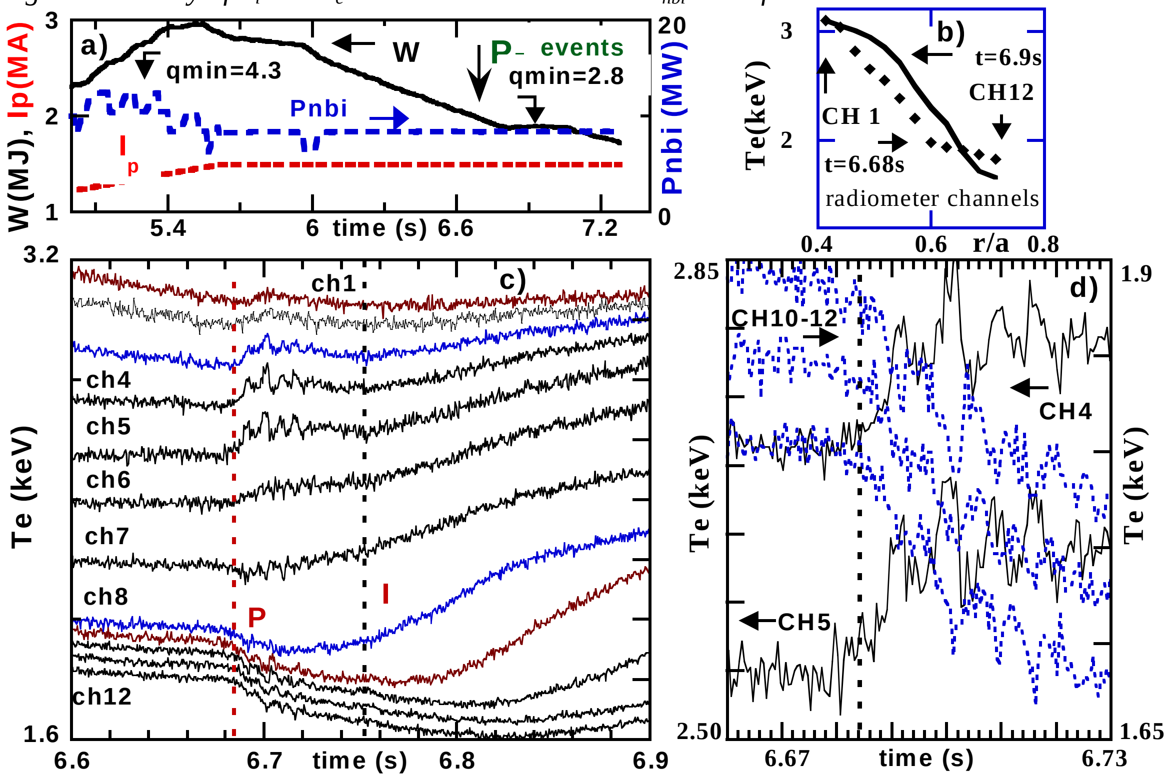
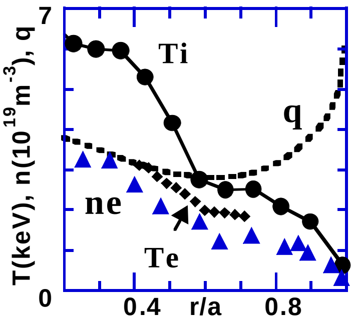



*Figure 2(a) Timetraces of W, $P_{nbi}$ and $I_p$ in shot 32474. Transitionless H-mode [10] starts from t ~5.7s. P- start of periodical ITB-events at $q_{min}$=3. (b) Positions of radiometer channels and $T_e$ (r) for t=6.68, 6.9 s. (c-d) $T_e$ timetraces at periodical P-ITB-events and ITB-event-improvement I*



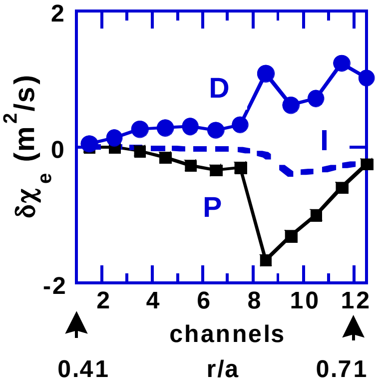




*Fig. 3. Profiles of $T_{e,i}$ ,$n_e$, and q before time P at Fig. 2.*

*Fig .4 Profiles of $\delta\chi_e$ estimated for P, I and D ITB-events*

degradation phase ($T_{e2-6}$ decay and $T_{e9-12}$ rise). At t=6.75s confinement improves again via the ITB-event I, and the ITB foot locates at the position of ch.11 at t=6.9s (see Fig. 2(b)) instead of position of ch8 before ITB-events. $T_i$ evolves similar to $T_e$, as usual. Profiles of $T_{e,i}$ (rhombus and circles), $n_e$ (triangles) q at t =6.9s (dotted line) are shown on Fig.3. The inversion radius (region between $T_e$ rise and decay at ITB-events on Fig 2(c) lies near the position of $q_{min}$, as usual [4-6]. The $\delta\chi_e$ profiles at ITB-events P, I and D (degradation which occurs later and not shown on Fig.2) were calculated from abrupt variations $\partial T_e/\partial t$ values at times of ITB-events (see method in [4]).

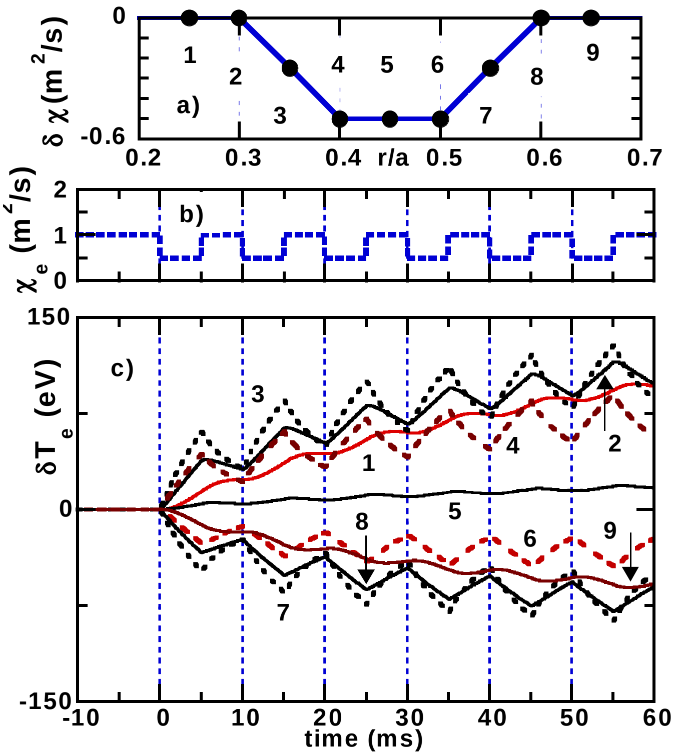



Fig. 5 presents modelling of periodical ITB-events with the profile of the electron heat diffusivity coefficient variation $\delta\chi_e$ shown in Fig. 5(a). The evolution of $\chi_e$ and calculated values of $\delta T_e$ at various radial positions are shown on Figs. 5 (b-c). The calculations reasonably describe the experiments shown on Fig. 2(c-d). We suppose that the periodical "global" L-H-L transitions with 20ms period (10ms H-mode phase and 10ms L-mode phase) found in JET [11] are clear physical analogue to the periodical ITB-events described above.

*Fig. 5 Simulation of P-ITB-events (a)$\delta\chi_e$ profile, (b) evolution of $\chi_e$ in time (c) evolution of $\delta T_e$.*

## 3. ITB-events under small NBI power in RS

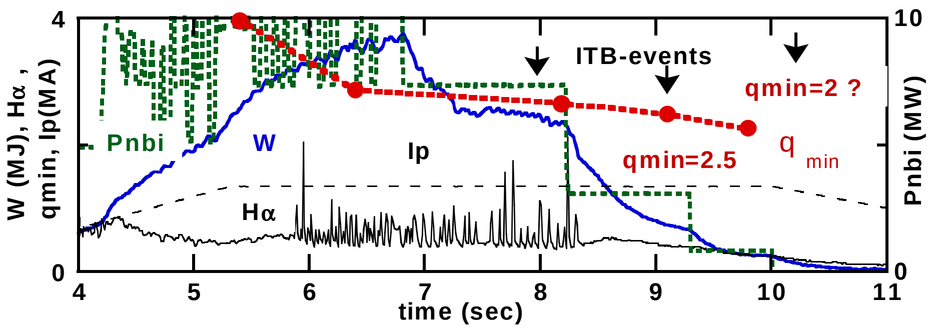



*Fig.6. Timetraces of $I_p$,W, $H_\alpha$ , $P_{nbi}$ and $q_{min}$ in shot 36639*

Under smaller power, ITB-events (in ~20 pulses studied) are connected with some low order rational $q_{min}$ values. ITB-events are found at $P_{nbi}$= 2.5MW in the latest phase of RS discharge 36639 (1.4MA /3.8T) under $q_{min}$=2.5 (see Fig. 6).

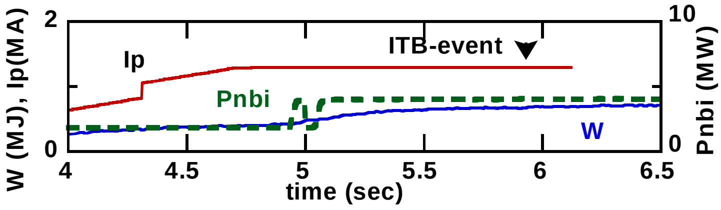
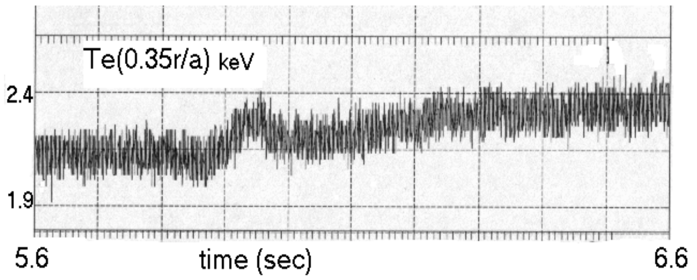



*Fig. 7 Timetraces of $I_p$, W and $P_{nbi}$ in shot 38976*

Moreover, the influence of some low order rational $q_{min}$ values is seen clearly for temporal ITB creation on $T_e$. The timetraces of shot 38976 (1.3MA/3.7T) are shown on Fig.7. The abrupt rise of $T_e$ is seen only once at $q_{min}$=3.5 at t=5.87s while more cases of $T_i$ rise are observed (after t=6.1s also). The timetrace of the row heterodyne data is shown on Fig.8. The rise of $T_e$ is seen at t=5.87s ($q_{min}$=3.5 at this time)




**$q_{min}$ =3.71------ 3.42-------3.22------------------------ 2.7**

*Fig. 8. Timetrace of $T_e$ (0.35), similar behavior seen at 0.2<r/a<0.4 region in shot 38976*

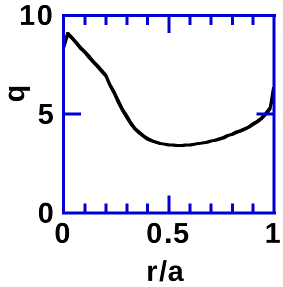



*Fig. 9. Profile q at t=5.9 s with qmin=3.42 in shot 38976*

in the wide region 0.18<r/a<0.42. The profile of the electron heat diffusivity variation $\delta\chi_e$ is obtained from abrupt variation of $\partial T_e/\partial t$ values at t=5.87s in the same way like described in detail in [4] and is wide in space (in the region over 0.5r/a). The q profile at t=5.9s is presented on Fig. 9. The wide region of small shear is observed clearly. In this particular shot 38976 case, $T_i$ evolves similar to $T_e$ at $q_{min}$=3.5 and rises separately from $T_e$ at t=6.1s (see Fig.10). The same behavior of $T_e$ and $T_i$ is observed in the similar shot 38974. The rise of $T_e$ occurs at t=5.92 s (close to t=5.86s in shot 3896).

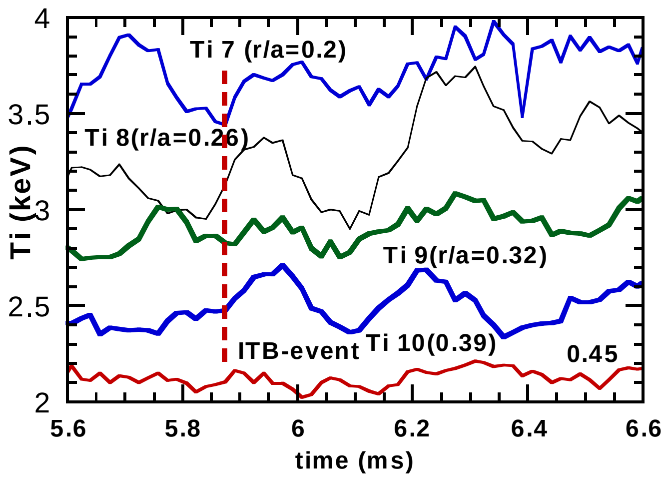



*Fig. 10 Timetraces of $T_i$ in shot 38976*

The difference of the $T_e$ and $T_i$ evolution seen regularly under the low power, suggests decoupling of $T_e$ and $T_i$ transport.

## 4. Discussion and Conclusions

Besides well-known formation of ITBs near q=2,3 surfaces in NrS or optimized shear discharges of JT-60U and JET [1-2], similar features are sometimes seen in small machines with ECR heating. The existence of the zones with improved transport near low-order-rational q values was reported at RTP [13]. The zone of the improved transport formed by off-axis ECRH in T-10 (the region with low shear and q near 1 inside ~0.3r/a) is able to survive at $R/L_{Te}$ = Rgrad $T_e$ / $T_e$ up to 23 with $\chi_e$ ~0.1-0.2 $m^2/s$ [14].

Under sufficient power in RS JT-60U plasmas, the space-time evolution of $T_e$ and $T_i$ due to series of ITB-events improvements and degradations is similar even being strongly varied in time and space. The same physical mechanism(s) is responsible for $T_e$ and $T_i$ evolution at ITB-events. ITB-events are observed under various values of $q_{min}$. The periodical ITB-events with ~8ms period are found in H-mode RS plasmas under crossing $q_{min}$=3. Probably the clearest analogues are periodical "global" L-H-L transitions with 20ms period found in JET [11].

Under smaller power in JT-60U RS plasmas, the space-time evolution of $T_e$ and $T_i$ could be different from each other. The transport looks different for $T_e$ and $T_i$. The influence of some low order rational $q_{min}$ values is seen clearly for temporal creation of the ITB on $T_e$ and for series of small-scale ITB-events on $T_e$. At present, we observe ITB-events at low order rational $q_{min}$ values only.

ITB-events triggers could be different in various JT-60U plasmas. The role of MHD-activity as ITB-event improvement trigger should be studied in future. The correlation of the MHD-activity and ITB-event improvement within a millisecond timescale was found sometimes (not frequently). The correlation of the coupled edge-core MHD-activity and ITB formation (unfortunately within ~100ms time interval) was reported on JET [11]. A physical mechanism of non-local bifurcations of the core transport at the ITB-events is still unclear. Further study of ITB-events (especially in low power cases) and ITB-events triggers is necessary.

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