

Study of ITB formation near $q=1$ surface in new ECRH/ECCD experiments at T-10 Tokamak

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In T-10 the role of $q=1$ surface has been demonstrated in many papers. T-10 is small tokamak with $R=1.5\text{m}$, $a_{\text{limiter}}=0.29\text{-}0.34\text{m}$. ITB was recognized by analyzing the slow heat pulse propagation (HPP) induced by central ECRH-onset in a sawtooth-free plasma created by off-axis ECRH at the first and the second harmonic [1-2]. ITB was formed near $q=1$ surface. The abrupt non-local reduction of transport in a central part of plasma column often occurs together with the appearance [3] (or slightly before [4]) of $q=1$ surface in T-10 sawteeth-free plasmas created by off-axis ECRH. We suppose that $q=1$ surface lies at the sawteeth inversion radius r_s , as usual. The existence of the very narrow zone with the reduced transport of impurities at $q=1$ surface has been reported in [5]. The existence of ITBs at $q=1.5, 2$ has been reported in T-10 PEP mode [6]. The role of magnetic shear and $q_{\text{min}}=1.5, 2$ was demonstrated in T-10 experiments with co/contra ECCD in the centre [7-8]. The reduction of the transport in the central region was caused by sawteeth at on-axis counter-ECCD [9]. Experiments with preprogrammed plasma motion performed in JT-60U RS plasmas, allowed analyzing fine details of $T_{e,i}$ profiles [10]. At the ITB shoulder, the transfer from flat T_e profile to a steep one ($\text{grad}T_e = 500 \text{ eV/cm}$) occurs within 3% of the minor radius.

1. Experiments with fast programmed plasma motion

A set of experiments with programmed plasma motion has been performed recently at T-10 in order to check the existence of ITBs near $q=1, 1.5, 2$. The time-linear shift of the plasma column has been realized in OH plasmas (up to 6cm per 60 ms) and plasmas with central ECRH (4cm per 60 ms) with absorbed power equal to 0.4 and 1 MW ($I_p=225\text{-}300 \text{ kA}$, $B_z=2.3\text{T}$, T_e up to 1.8 keV, $n_{e \text{ line av}} = 3 \cdot 10^{19}/\text{m}^3$). In the outer part of the plasma column the typical distance between the ECE channels is equal to 2.5 cm. Figure 1 shows the evolution of raw not-calibrated ECE data at the same channel during 4 cm outward shift at $P_{\text{ECRH}}=1\text{MW}$ in two similar shots with slightly different B_t – shot 64491 ($B_t= 2.35 \text{ T}$, $r = 12.5 \text{ cm}$) and 64494 ($B_t= 2.4 \text{ T}$, $r = 15.3 \text{ cm}$). The ECRH heating remains central during the outward shift and absorbed well inside inversion radius. The transfer from the gradient

zone outside the sawteeth inversion radius r_s to the flat T_e profile inside r_s typically occurs at a 1 cm distance. Thus, the spatial width of the ECE detectors lies near 1 cm. The evolution of T_e is nearly linear without any ITB signs. Rarely, the behavior of T_e looks slightly different. Figure 2 shows the raw not-calibrated data at two ECE channels at $P_{\text{ECRH}}=0.4$ MW. A very narrow and weak ITB near r_s (within errorbars) is probably observed at the upper curve. Roughly speaking, the spatial 1 cm width should smooth 0.5 cm ITB with double gradient into 1 cm region with the gradient value higher by 50%. No clear ITB signs at the $q=1$ surface have been observed in any of the 27 shots produced so far. In several shots, the existence of a narrow ITB with a 0.5 cm width and a doubled T_e gradient (within the errorbars) can be suggested.

2. ITB created by sawteeth oscillations almost damped by off-axis ECRH/ECCD

In T-10 L-mode with central ECRH, the rise of T_e outside sawteeth inversion radius r_s , typically fully decays during 1-2 ms after sawteeth crash. A new phenomena created by sawteeth oscillations almost damped by HFS off-axis ECCD has been found recently. Figures 3-4 shows the evolution of T_e during nearly damped sawteeth oscillations with long period. T_e rises near r_s after sawteeth crash. T_e value stays at the same level for 15-20 ms (see very clearly after some crashes at Figure 4) and heat pulse virtually does not propagate outside ($\chi_e^{\text{HP}} \ll \chi_e^{\text{PB}}$) for 15-20 ms. The local value of T_e rises by 40% in the narrow 3 cm zone. In our opinion, this fact means that the value of χ_e decreases by 40% while the value of $\text{grad}T_e/T_e$ rises by 35%. The value of χ_e becomes 2.5 times lower compared with the L-mode scaling. Figure 5 shows the evolution of the turbulence level during similar crashes. The reflectometer data shows enhanced level of turbulence after the crash. Later, at ITB formation, the level of turbulence falls slightly below its value before the crash.

3. Conclusions

A set of experiments with programmed plasma motion has been performed recently at T-10 in order to check the existence of ITBs near $q=1, 1.5, 2$. The time-linear shift of the plasma column has been realized in OH plasmas (up to 6cm per 60 ms) and plasmas with the central ECRH (4cm per 60 ms) with absorbed power equal to 0.4 and 1 MW ($I_p=225-300$ kA, $B_z=2.3$ T, T_e up to 1.8 keV, $n_{e \text{ line av}} = 3 \cdot 10^{19}/\text{m}^3$). In the outer part of the plasma column, the typical distance between the ECE channels is equal to 2.5 cm and the transfer from the gradient zone outside the sawteeth inversion radius r_s to the flat T_e profile inside r_s typically occurs at a 1cm distance. This fact means that the spatial width of the ECE detectors is close to 1 cm. No signs of clear ITB at the $q=1$ surface have been observed in

any of the 27 shots produced so far. In several shots, the existence of a narrow ITB with a 0.5 cm width and a doubled T_e gradient (within the errorbars) can be suggested.

A new type of ITB created by sawteeth oscillations almost damped by the off-axis co-ECCD/ECRH (with small 5-10 kA EC-driven current) has been found recently. A sawteeth crash causes the rise of T_e near r_s and heat pulse does not propagate outside for 15 ms. The value of χ_e decreases by 40% while the value of $\text{grad}T_e/T_e$ rises by 30%. The value of χ_e becomes 2.5 times lower compared with the L-mode scaling. The reflectometer data shows an enhanced level of turbulence after the crash. Later, at ITB formation, the level of turbulence falls slightly below its value before the crash.

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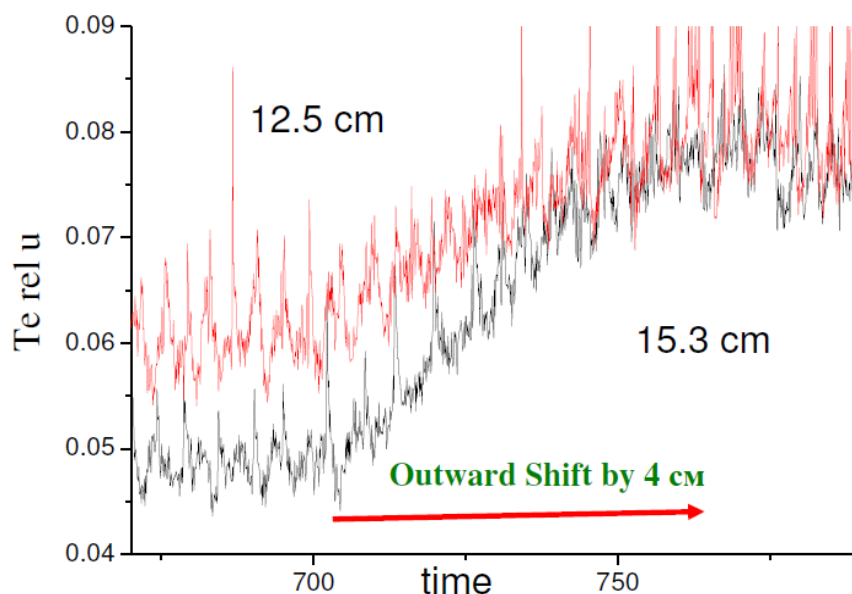


Figure 1 Evolution of raw not-calibrated ECE data at one ECE channel during 4 cm outward shift at central $P_{\text{ECRH}}=1\text{MW}$ in two similar shots with slightly different Bt – shot 64491 (Bt= 2.35 T, $r = 12.5$ cm) and 64494 (Bt= 2.4 T, $r = 15.3$ cm – clear transition to flat zone at inversion radius, no signs of ITBs

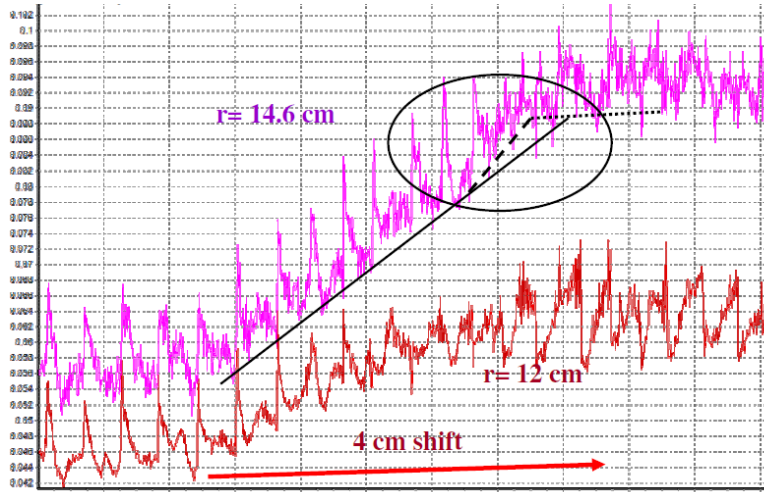


Figure 2 Evolution of raw not-calibrated and non-time averaged data (the time resolution is 1 microsecond) at two ECE channels during 4 cm outward shift (during 60 ms) at central $P_{\text{ECRH}}=0.4$ MW. Dotted line shows the signs of the very narrow and weak ITB near r_s (within errorbars).

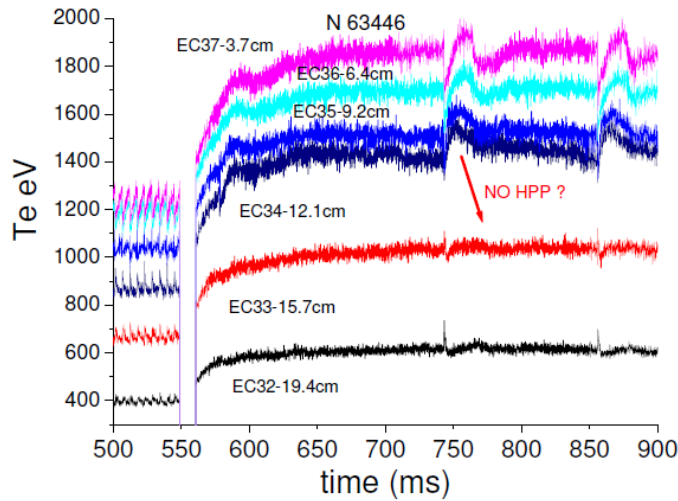


Figure 3 T_e evolution during nearly suppressed sawteeth oscillations (ECE at LFS) under HFS off/axis ECCD in shot 63446 ($I_p=220$ kA, $B_t=2.15$ T $P=0.9$ MW, $n_{\text{line av}}=1.8$). T_e rises inside $r=12$ cm and perturbation does not propagate outward during 15 ms after sawteeth crash with very long period.

Figure 4 Evolution of raw not-calibrated data in slightly different shot 63447. T_e rises at $r=13$ cm after sawteeth crash (near inversion radius) and nearly does not decay during 15-20 ms.

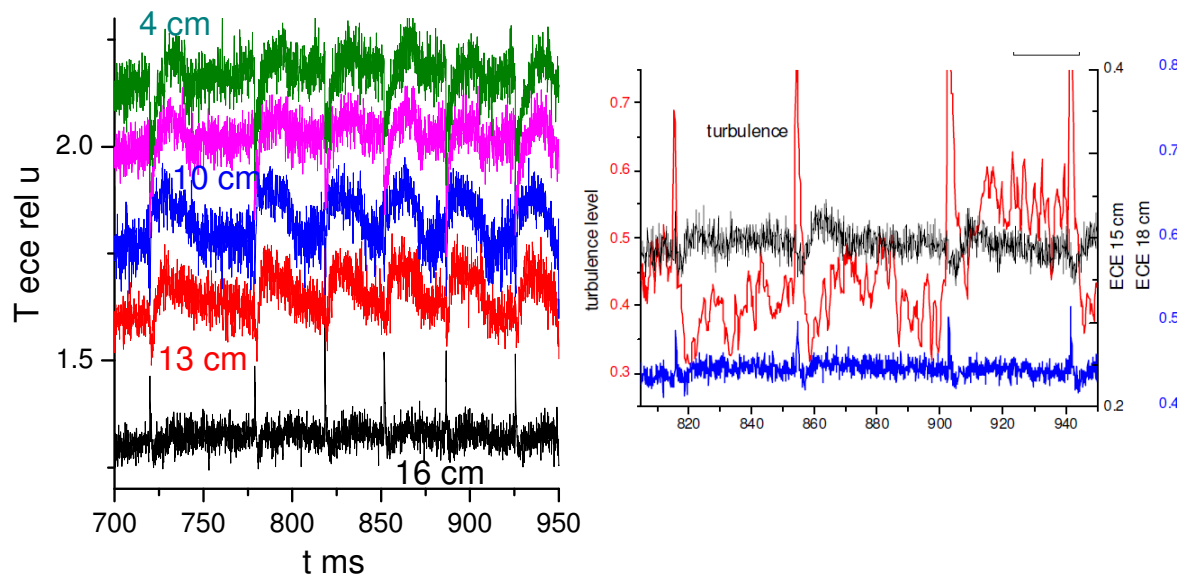


Figure 5 Turbulence study (red curve) during T_e evolution - shot 66049 ($I_p=250$ kA, $B_t=2.15$ T $P=1$ MW, $n_{\text{line av}}=3$) - 6kA ECCD (0.6 MW -toroidal angle 8 degree, 0.4 MW-0 degree), raw ECE (15cm-black curve) - near the outer edge of ITB, ECE(18cm)- blue line