

Investigation of the electron internal barrier formation mechanism in T-10 tokamak

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On T-10 tokamak $q(r)$ profile was controlled by ECR heating/current drive. The gyrotron set with frequency $f=140$ GHz and absorbed power up to 1 MW was used. In Ref. [1] the following criteria for the electron internal transport barrier formation (EITB) were obtained: $dq/dr = 0$ for the safety factor value near the rational one. Using them, we organize EITB at $r/\alpha_L=0.5 - 0.6$ (α_L is the limiter radius) by shift of ECR position to the high field side, so the magnetic field was decreased. This allows us to measure the plasma potential distribution in the outer half of the plasma radius by Heavy Ion Beam Probing (HIBP) [2]. The plasma current was relatively high ($I_p=180 - 310$ kA), so q at the limiter was low ($q_L=2 - 3$). The electron temperature profile, T_e , was measured both by Thomson scattering and ECE methods. Besides the radiointerferometer, the electron density profile $n_e(r)$ was measured at the plasma edge by radiorelectometry and from HIBP intensity changes.

The time evolution of plasma parameters is presented in [fig. 1](#). The transition to the enhanced confinement is accompanied by increase of $T_e(0)$, β_p and n_e and decrease of D_α line intensity – the features typical for the L-> H transition. In [fig. 2](#) and [3](#) the radial distributions of plasma parameters are represented for two cases: before and after the transition. After the transition $T_e(r)$ profile strongly changes near $\rho=0.6$, where the steep T_e gradient is formed. The steepest $n_e(r)$ gradient is formed in the limiter vicinity. The sawtooth reverse phase radius, r_s , increases during the transition from $r_s=10$ cm to $r_s=13$ cm. [Figure 4](#) shows changes of the sawtooth heat pulse propagation speed outside r_s . This speed decreases dramatically inside the internal transport barrier (ITB) region (the region of high ∇T_e), demonstrating decrease of heat conductivity in this part of the plasma. The radial profiles of plasma potential $\phi(r)$, measured in the ITB region for different instants, shown in [fig. 1](#) by arrows, are presented in [fig.2-b](#). The potential was counted from the level obtained before the transition in the given plasma point. In [fig 3-b](#) the same for the edge zone, where the density gradient is formed, is presented. In both regions the potential well is formed during the barrier formation. When the process has reached the quasi-steady state, the potential wells changes, making potential decrease in the ITB region to the inner part of plasma. The ion temperature, T_i was low due to the weak thermal contact between electrons and ions for this relatively low density, but T_i increased in the core during the barrier formation ([fig. 5](#)). The estimation shows that the ion confinement time increases in a factor of 1.5.

In the T-10 the auxiliary ECR power was absorbed by electron component only. This power does not input the angular momentum. We can believe that we created the *electron*

transport barriers, and any possible modifications of the ion component are secondary effects relatively to the electron processes. **Figure 6** presents $q(r)$ profile for the shot shown in **fig. 4**. The profile calculated for the experimental $T_e(r)$ and $n_e(r)$ using the equation of the poloidal field diffusion and the neoclassical resistivity. The wide zone with $q \leq 1$ and a low q value at the edge leads to a small interval of errors. As it was underlined in [1], $q(r)$ profile in these experiments has a plateau in the barrier zone; in this case it lies near the value $q(r) \approx 1$. Note that we do not need in any negative shear for the barrier formation. Simultaneous formation of two transport barriers was noticed in experiments with $q_L \leq 4$. Even in the case when internal barrier was periodically formed in the central part of the plasma ($r_{ITB} = 8 - 9$ cm), the effects of edge confinement increase may be seen (**fig. 7**).

We may argue that at least in our experiments ($q_L \leq 4$, that is the edge plasma sufficiently intensively interacts with the limiter) the EITB formation **always** is accompanied by formation of the edge barrier with all typical features of the H-mode.

We can propose the following explanation of observed phenomena: The non-linear interaction of the magnetic islands leads to their splitting and, possibly, the small-scale turbulence arises. This determines the plasma profiles self-consistency and non-local dependencies of the transport coefficients [3]. The shear $S \equiv r/q \, dq/dr = 0$ near some islands may disconnect them and the ring with unperturbed magnetic surfaces and reduced (but many times greater than classical) electron transport arises. The electron flux is reduced at the unchanged ion flux; this results in appearance of the potential well in the zone of reduced electron transport and in equalisation of the fluxes. The considerable radial electric fields appear and occurs the poloidal plasma drift with velocities, which are rapidly changed along the radius, and even they change the direction (the sheared flow). This results in stabilisation of some modes important for ions (may be the ITG mode [4]) and improvement of their confinement. Owing the toroidal mode coupling, the conditions for the barrier formation may be fulfilled simultaneously at some rational surfaces. The plasma cooling near the outer rational surface due to interaction with the limiter and the wall is also favourable to the $q(r)$ special profile (with “shoulder”) formation at the plasma edge.

Conclusions:

1. The internal transport barrier is formed with such a current distribution, where $dq/dr \approx 0$ and q near the rational value.
2. During the barrier formation, a deep narrow potential well occurs, which manifests the improvement of the electron confinement in the barrier zone.
3. At $q_L \leq 4$, two barriers appear simultaneously. The external barrier has the features of the L-H transition.

Acknowledgement

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References

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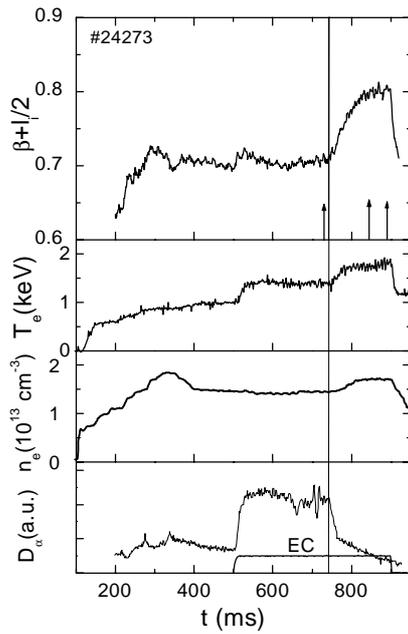


Fig. 1. The time evolution of the plasma parameters in the regime with simultaneous formation of the internal barrier at $r=17$ cm and the $L \rightarrow H$ transition.

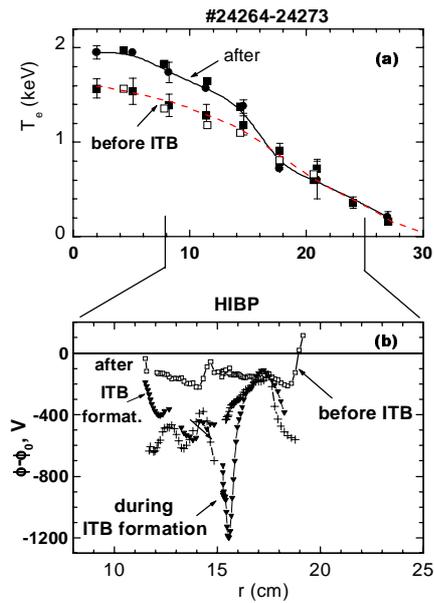


Fig. 2. The electron temperature profile from Thomson scattering (circles) and 2-nd ECE harmonic (squares) (a); the relative potential profile (b) before, during and after the barrier formation. Time instants of potential measurements are shown in Fig.1 by arrows.

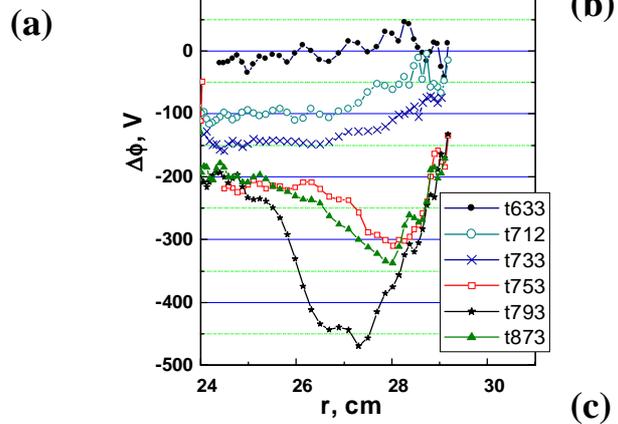
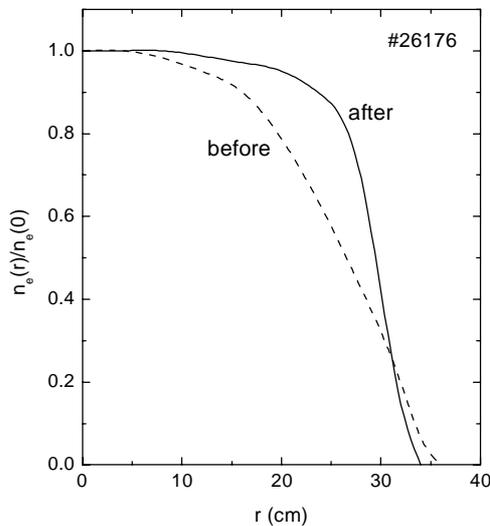


Fig.3 The shot with two barriers;
 (a) the density profiles before and after the barriers formation;
 (b) evolution of the relative plasma potential at the edge;
 (c) the barrier formation at $t > 670$ ms is seen on different plasma parameters. Dotted lines show the moments of the potential measurements.

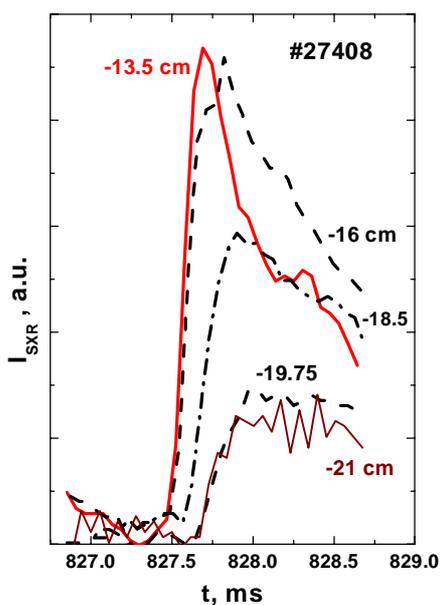


Fig. 4. The heat pulse from the sawtooth crash measured by SXR rapidly propagates at $r < r_{ITB}$ and slowly pass through the barrier zone.

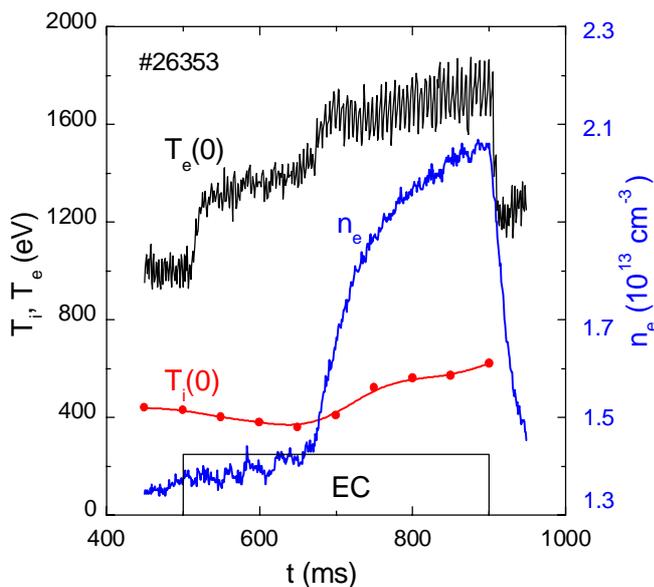


Fig.5. The temporal evolution of the central electron and ion temperatures, and line-averaged density during the internal transport barrier formation.

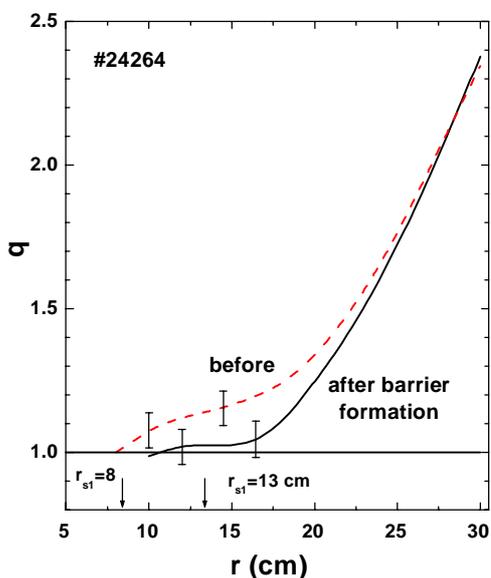


Fig. 6. Calculated $q(r)$ profile before and after the ITB formation. Bars show estimated range of errors. Arrows show radii of sawtooth inversion from SXR measurements.

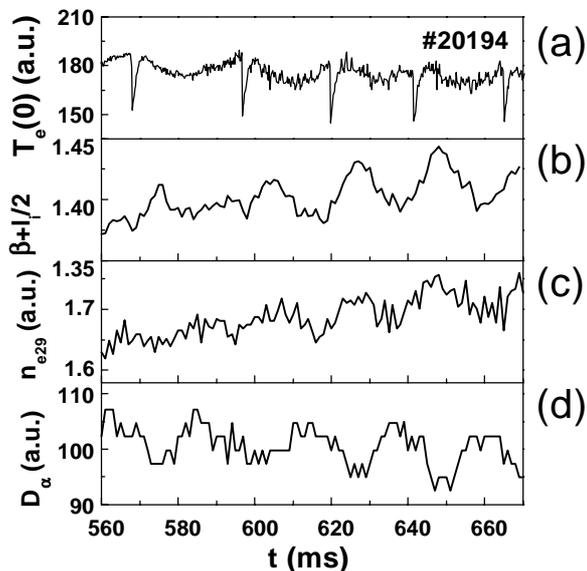


Fig. 7. Periodical growths of the central electron temperature (a), relative pressure (b) and line-averaged density at outer chord $r=29$ cm (c) during humpbacks accompany by drops of $D\alpha$ line emission (d) that point out to temporary improvement of confinement