PECULIARITIES OF PLASMA BEHAVIOR IN THE VICINITY OF RATIONAL q_{min} VALUES

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Last years in many world tokamaks (see for example [1,2]) the investigations of the radial q(r) distribution influence on plasma confinement were carried out. It was shown that special conditions exist, in which plasma confinement may be increased some times due to appearance of internal thermal barrier (ITB), i. e. the local region of reduced thermodiffusitivity χ_i and χ_e. The ITB arises in the experiments with negative shear, $S \propto$ dq/dr<0, formation. The region of χ_i and χ_e minimum is near the dq/dr=0. In large tokamaks, such as DIII-D, TFTR, JET and other, the powerful auxiliary heating was switched on during the current rump stage of discharge. Due to current reconstruction processes it permits to organize relatively wide zone of the negative shear. The ITB formation in such experiments the theory explains by the stabilizing influence of negative shear plus enhancement $\mathbf{E} \times \mathbf{B}$ rotation flow sheared in ITB region. But in some experiments ITB may be organized even without S<0 region [2], but dq/dr≅0 is need. Under the conditions of powerful but not local methods of plasma heating and current drive it is not simple carefully to investigate the processes at the beginning of ITB formation. The possibility of current density profile control by the ECCD permits to perform in T-10 tokamak detailed investigations of internal MHD activity for different q(r) profiles. Two examples of such profiles are shown in Fig.1. A number of peculiarities of plasma behavior were observed when $q(r)_{min}$, increasing, approaches to a rational value: m/n= 1; 1.5; 2… There are: 1. Transition from sawtooth relaxation into "humpbacks" [3,4,5].   2. "Hills" [4,5,6]. 3. Transition to steady state with better confinement [3].

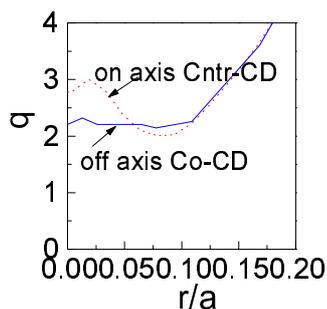If q_{min} overcome given rational value similar effects appear near the next rational value.

Fig.1. Calculated typical q(r) profile for on-axis CntrCD (B=2.46T, I=79kA, n_e=1.1*10^{19}m^{-3} and off-axis CoCD (B=2.3T, I=75kA, n_e=1*10 ^{19}m^{-3}) for q_{min}=2.
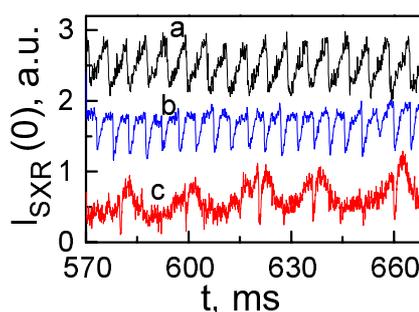

Fig.2. Sawtooth form changes under q_{min} increase (from up to down).

Humpbacks. When dq(r)/dr is near 0, but not =0, at q near (lower) 1 or 2 the humpbacks appear instead of usual sawteeth. (Fig.2). Radial symmetric temperature increase takes place. Simultaneously $I_{D\alpha}$ decreases, β_p increases, n_e(r) remain to be constant, so total confinement increases. Then internal disruption takes place after which T_e increase again very rapidly,

demonstrating high confinement inside the central region. But after some time T_e decreases again to the initial level before the humpback.

Hills. Further q_{min} approach to the rational value leads to internal disruptions disappear, but periodical central T_e increases still exist (Fig.3). This "hills" are the most pronounced near q_{min}=2. But they also may be seen in some conditions near q_{min}=1. The T_e fluctuation in hills may reach 25%. A total confinement in hills increases. Both hills and humpbacks are accompanied by sinusoidal fluctuations with a frequency about a few kHz (Fig.4). Near q=2 they are in phase at up and down from the center of plasma. (m=2). The fluctuations are seen at on-axis CntrCD only. During T_e increase fluctuations are seen near the reversal phase radius. During T_e decrease they are seen in the central part. It may be means that MHD
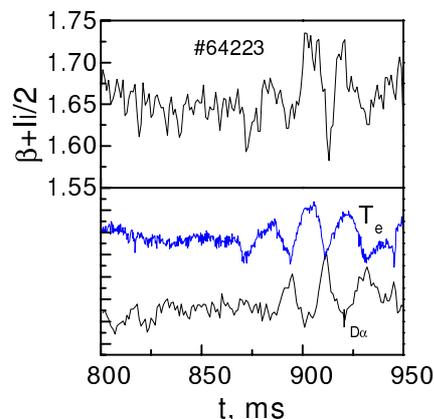

Fig.3. During hills T_e and β_p +li increases and $I_{D\alpha}$ decreases.

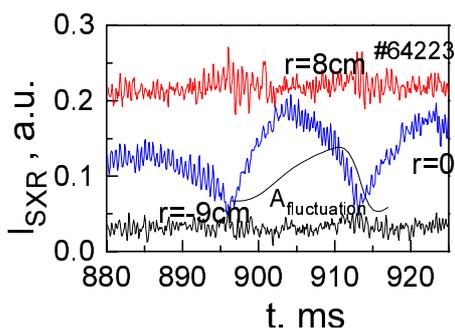. islands configuration changes during the hill process. In any case it means that q_{min}<2 in this case.

Fig.4. MHD activity (m=2) during hills. The MHD activity displaces from r=9cm to central part of plasma Solid curve is an amplitude of fluctuations during one hill period for the central chord.
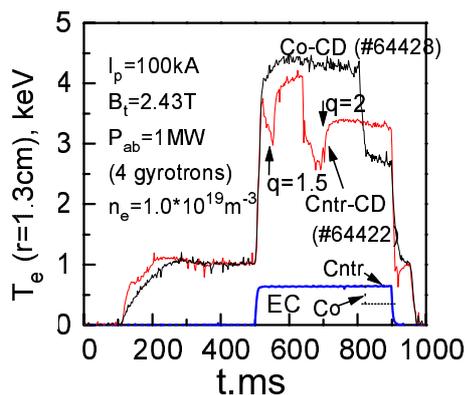

Fig.5. The example of two ITB formation for on axis CntrCD at q_{min} =1.5 and q_{min}=2 (q_{min} increase in time).

Steady state enhancement confinement. Farther small increase of q_{min} leads to the steady state enhancement confinement. The T_e(0) increase is of the same order as hills amplitude. Sometimes this transition begins after one or two hills. The effect is clearly seen for q_{min} value near 1.5 and 2 (Fig.5).

No rotation speed change was registered during this transition (The speed of fluctuation rotation was measured by the reflectometry method. It was low: ω=1–3 10^3 s^{-1}).

The transition effect may be seen either at on-axis CntrCD, or at off-axis CoCD for resonance at the high field side. As q(r) in these experiments was different (Fig.1) one can conclude that the transition does not depend on negative shear existence.

ITB behavior after switching off a part of EC power. When two of four operating gyrotrons are switched off in the shot, in which internal barrier has been formed, T_e(t) and I_{SXR}(t) decay more slowly inside the internal barrier surface, faster – outside it (Fig.6). The high gradient of T_e is maintained inside the barrier region during a few energy confinement times. Then the barrier disruption takes place. In the case of off-axis CoCD one can observe

smooth T_e decay without internal disruptions. In the case of on-axis CntrCD internal disruptions take place during T_e decay, but at the beginning they do not destroy the barrier. In the experiments, in which ITB was not organized, for example with off-axis CntrCD (Fig.6 #20921) T_e decay in the plasma occurs in accordance with energy confinement time. As for given experiment the power of two gyrotrons was not enough for the ITB formation, we can suggest that the effect may be bound with q(r) redistribution time.
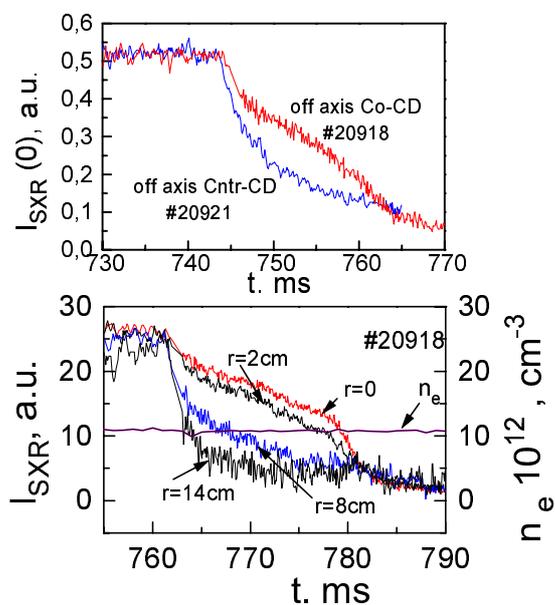

Fig. 6 Time evolution of I_{SXR} for different chords after switching off 2 to 4 gyrotrons.
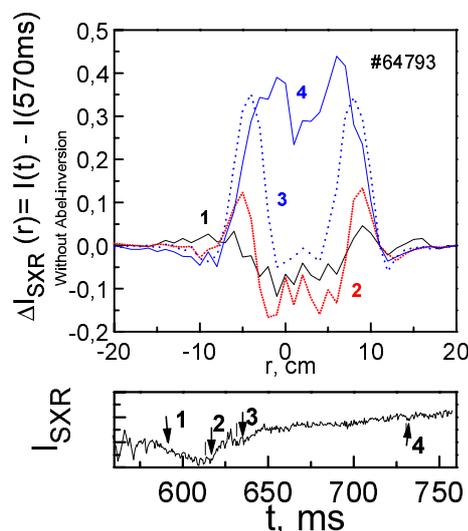

Fig.7. SXR intensity profile changes in relation t=570ms during ITB formation.

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The experiments show that in all cases electron temperature T_e and soft X-ray intensity I_{sxr} increase are radial symmetrical. It begins in a ring near the rational surface (Fig. 7). Outside of this surface and in the plasma center T_e decreases at the beginning even when EC power is deposited in the plasma center (on-axis CntrCD). After the ITB has been already formed the T_e increase spread to the center. The total energy confinement increases, but not strongly.

DISCUSSION.

   In these T-10 experiments one can speak about electron component behavior only. Ions remain to be relatively cold, having bad thermal contact with electrons at low n_e and high T_e. Totality of the experimental results shows that in given conditions the surface with low electron thermodiffusivity, or in other words, ITB may be formed. This is confirmed also by careful experiments in RTP [7,8].
   Let us do two suggestions:
1. *Internal disruption is possible when q, being near the rational value, has dq/dr> some value K (which may be a function of plasma parameters).*
2. *In the case when dq/dr=0 (or near it) under q≤1; 1.5; 2...ITB arise in the narrow region.*
   Now we can explain all the described phenomena.
   The ITB formation begins from T_e increase in the ring inside the region, limited by a rational surface. Redistribution of $T_e(r)$ leads to increase of dq/dr>K near this surface and to internal disruption appearance. Further current density redistribution due to T_e rise destroys q(r) profile, which is need for internal barrier existence and hence destroys the internal barrier. Thus humpbacks arise in the case when condition for ITB formation is hardly performed. When $T_e(r)$ redistribution can not lead to dq/dr>K, hills are seen. When dq/dr becomes near

zero in the wide enough ring, and the confinement enhance does not destroy the necessary for ITB q(r) profile, the internal barrier can exist stationary. Existence of MHD fluctuations near the ITB position (Fig.4), show that q_{min} at the internal barrier surface is little less then the resonance value. Many experiments in other tokamaks show (see for example [2]) that the presence of a negative shear region is not important for ITB formation. Why the ITB associated with dq/dr≅0? One of possible explanation: MHD islands, which interact with each other at their edges, determine usually plasma confinement. Due to this the real MHD structure may be very complicate. It may leads to a good thermal contact between different parts of the plasma. As a result we have the "profile consistency" and L-mode transport coefficients. To decrease islands interaction one needs either to decrease its dimension by high shear in the island region or to enlarge the distance between them. Low dq(r)/dr, at given q value, disjoins the MHD islands, preventing their thermal contact, and so creating ITB. (The theory of such process is given, for example, in [9]).

There was no strong plasma rotation shear in T-10 experiments because ECRH does not insert into the plasma any momentum, and the deposited power was not high enough to increase rotation speed by a steep ∇p. May be due to this the barriers were not high.

CONCLUSION.

1. Minimum of the electron thermodiffusivity (ITB) appears on the magnetic surface, for which q has a value approaching to the rational, and dq(r)/dr≅0. Periodical and stationary ITB appearance is not bound with S<0.

2. It is probable that dq/dr slides apart the MHD islands, preventing thermal contact between them, and so creating ITB.

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