PECULIARITIES OF PLASMA BEHAVIOR IN THE VICINITY OF RATIONAL $q_{\text{min}}$ 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 thermodiffusivity $\chi_t$ and $\chi_e$. The ITB arises in the experiments with negative shear, $S \approx dq/dr<0$, formation. The region of $\chi_t$ and $\chi_e$ 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 ramp 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 $E \times B$ rotation flow sheared in ITB region. But in some experiments ITB may be organized even without $S \approx 0$ 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 $q(r)_{\text{min}}$, 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 $q_{\text{min}}$ 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 $q_{\text{min}}=2$.

![Fig.2. Sawtooth form changes under $q_{\text{min}}$ increase (from up to down).](image)

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 $I_{\text{SXR}}$ decreases, $\beta_n$ 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 islands configuration changes during the hill process. In any case it means that $q_{min}<2$ in this case.

![Fig.3. During hills $T_e$ and $\beta_p * li$ increases and $I_{Dq}$ decreases.](image)

**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: $\omega=1–3 \times 10^3 s^{-1}$).

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.

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 \( dq/dr > 0 \).\( dq/dr > K \) (which may be a function of plasma parameters).

2. *In the case when \( dq/dr = 0 \) (or near it) under \( q \leq 1; 1.5 \) ... 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 $q_{\text{min}}$ 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 complicated. 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 $\nabla p$. 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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