Tearing modes and transport barriers

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In ITBs plasmas it is often observed MHD activity on the top of transport barriers that appears in the form of magnetic islands, internal disruptions and ELM’s. Analysis of the experiment shows that there is the link between transport barriers formation and development of the MHD modes. This link deals with the mechanism of transport barriers triggering and the main properties of plasma self-organization. In the work [1] an analysis of regimes with transport barriers and estimations of poloidal numbers of turbulent modes near transport barriers have been performed. The assessment of spectrum of the poloidal mode numbers was based on the mechanism of transport barrier formation. According to this approach the transport barriers are formed in the vicinity of low order q surfaces in gaps between adjacent rational magnetic surfaces, which arise for modes with \( m < m_1 \), where \( m_1 \) determines the low boundary of the turbulent spectrum inside the barrier [1]. The width of the gap depends on the mode number and scales as \( \delta_{\text{Gap}} \sim (m_q dq/d\Gamma)^{-1} \) (1). By comparing of the gap width with the width of the transport barrier obtained from the experiment one can estimate boundary value \( m_1 \). Calculations of \( \delta_{\text{Gap}} \) for various \( m \) were performed by using experimental q profiles.

Turbulence characteristics depend on the value of the heating power \( P \). To examine this dependence the data from different tokamaks have been analyzed. In fig. 1 the empirical dependence of modes numbers \( m_1 \) on the heat flux density \( \Gamma = P/S \), where \( S \) is the magnetic surface area, is presented. The dependence \( \Gamma(m_1) \) shows that in the highly self-organized tokamak plasma under high heat fluxes the modes of lower numbers are exited, while lower heat fluxes correspond to the higher modes numbers. On the KSTAR tokamak the direct measurements of poloidal numbers of MHD modes in H mode regimes has been performed using ECE imaging diagnostic in 2D [2]. For the thermal flux density \( \Gamma = 0.03 \text{ MW/m}^2 \) the poloidal mode number \( m = 40 \) was found on the top of external transport barrier near \( q = 6 \). The corresponding point is plotted in fig. 1 (red star). It is seen that obtained experimental result is in accordance with the dependence \( \Gamma(m_1) \). Increase in fluctuations of turbulent modes can cause appearance of magnetic islands. Enhancement of fluctuation can be connected with the mechanism of barrier formation due to dependence of intensity of transport barrier on magnetic shear and
numbers of participating modes through the $\delta_{\text{gap}}$ width (1). The link between MHD modes and transport barriers has been experimentally studied in ITBs plasmas of the T-10 tokamak. A series of experiments with $q$ profile control has been carried out pointed to ITBs formation. The ITBs were produced by application of off-axis ECRH and plasma current ramp-up. Fig.2 shows the electron temperature profile in the shot #56974. Destabilization of MHD modes is observed on the top of the transport barrier which is located near $r=16$ cm. The main parameters of the discharge are as follows: magnetic field $B=2.1$ T, the plasma current $I_p=160$ kA, the central line-average density $n_e=1.9 \times 10^{19}$ m$^{-3}$, heating power of off-axis ECRH $P_{\text{ECRH}}=0.9$MW. The plasma current was raised from $I=160$ kA to $I=210$ kA at $t=(690-700)$ ms. As it is seen on the time traces of ECE signals (fig. 3) the magnetic islands develop at $r=16$ cm. Corresponding spectrogram for the ECE channel $r=16$ cm are shown in fig.4. Transport barrier development takes place during $(700-730)$ ms and it is seen that the onset of MHD modes occurs at $t=730$ ms after barrier formation. After appearance of magnetic islands the $q$ profile flattens (fig.5) and the zone of the gap and the barrier moves outward. The $q$ profile flattening increases $\delta_{\text{Gap}}$ according to the formula (1) that should lead to the transport barrier growth. Indeed, following a sequence of internal disruptions and changing of the modes frequency (from $7.5$ kHz to $5$ kHz) during $t=(750-770)$ ms, the transport barrier increase after $t>800$ ms takes place at the same time with development of MHD oscillations at $r=16$ cm (fig.4). The experiment shows that magnetic islands appear after barrier formation, and development of both the transport barriers and magnetic islands is characterized by complex dynamics which reflects
their relationship. The main frequency of MHD modes is 5 kHz and taking into account rotation velocity $V_{pol} \approx 2 \times 10^4$ rad/s one can obtain the mode numbers $m/n = 3/2$ that develops at $q = 1.5$. Thus on the top of internal transport barrier develops the main harmonics of MHD modes corresponding to the number of low order RMS near which the transport barrier is formed unlike in the case of the external transport barrier where the mode numbers of magnetic islands was higher than numbers of magnetic surfaces on which they were developed [2]. The result could be explained by evolution of primary magnetic islands under high thermal fluxes in the core plasmas. Experimental study of dependence of modes numbers on the value of thermal fluxes is possible in sawtoothing plasma. The evolution of MHD modes spectrum has been observed during the ramp phase of internal disruptions for two cases with different additional heating power. The scenario of experiment (#61406) includes two stages of application of injected $P_{ECRH}$. ECRH power $P_{ECRH}=0.5\text{MW}$ was applied at $t=550$ ms and $P_{ECRH}=1.4\text{MW}$ was applied at $t=650$ ms. The main parameters were $B=2.4\text{T}, I_p=220\text{kA}, n_e=3.5 \times 10^{19}\text{m}^{-3}$. In the discharge with such scenario a strong ITB near $q=1$ was formed and magnetic islands were developed on the barrier top at $r=10\text{cm}$ located inside the sawtooth inversion radius. Fig.5 shows the fist case of plasmas with $P_{ECRH}=0.5\text{MW}$ ($t=550-650$ ms). In ramp phase of ST restoration of magnetic surfaces and transport barrier is accompanied by appearance and development of magnetic islands with frequency $f=2.5$ kHz. The growth of magnetic islands is terminated by ST crash.
ECRH plasmas with $P_{\text{ECRH}}=1.4$ MW (fig.6, t=650-750ms) under higher heat fluxes complex picture of MHD modes development is observed where fluctuations with different frequencies co-exist during the ramp phase of ST. Inside the $m/n=1$ islands rotating with frequency $f\sim5$ kHz the modes with higher frequency ($f\sim50$ kHz) are clearly seen. Their mode number can be estimated as $m \sim 10$.

Corresponding point was plotted in fig.1 (blue star) taking into account the heat flux density $\Gamma \sim 0.75$ MW calculated at $r=10$ cm. It is seen a good agreement of obtained number of fluctuating modes with the dependence $\Gamma (m_1)$.

This dependence reflects the crucial role of thermal fluxes in self-organization in spectrum of fluctuations. Self-organization in tokamak plasmas is characterized by conservation of the normalized pressure profile $P_N(r)$ [3]. From this viewpoint excitement of MHD modes in ITBs plasmas deals with local distortion of $P_N(r)$ due to barriers formation. The link between magnetic islands and transport barriers is determined by complex dynamics of the non-linear loop. Injected heating power controls the thermal fluxes and spectrum of fluctuations. Under heat fluxes transport barriers form in gaps (1) near low order magnetic surfaces for exited turbulent modes with numbers $m < m_1$ and given $q(r)$. Reduction of the heat fluxes in gaps inside the transport barrier causes the energy increase on the barrier top, enhancement of fluctuations and appearance of magnetic islands. In its turn, development and evolution of magnetic islands leads to flattening of the current density and $q$ profiles. Changes of the numbers of participating modes and the topology of magnetic surfaces can cause an increase in transport barrier due to increased $\delta_{\text{Gap}}$ (1). The transport barrier growth leads to further rise of fluctuations energy. Such feedback cause internal disruptions that are observed in the experiment. Due to dependence on the value of $\Gamma$ these physical processes can determine the limit of the energy content (the limit on $\beta$).

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