MHD instabilities connected with transport barriers development

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Development of magnetic islands on the top of transport barriers (ITB's) is observed in experiments. Analysis shows that the link between ITB's and MHD instabilities can be connected with the mechanism of ITB's formation. Understanding of both the mechanisms of ITB's formation and magnetic islands development remains an urgent task. According to generally accepted approach the rotational shear that causes turbulence suppression is considered the main mechanism of transport barriers formation. But at the same time the question about mechanism of ITB's triggering remains open. In present paper we consider relationship between transport barriers and magnetic islands development as connected with special properties of rational low order magnetic surfaces and taking into account processes of plasma self-organization. Particular role of low order surfaces in ITB's formation was studied in experiments [1]. According to this mechanism ITB's appear in the vicinity of integer (semi-integer) rational surfaces of low numbers q=1, 1.5, 2 … in gaps created due to rarefaction of resonant surfaces. This mechanism was considered to be important for the case of zero or low magnetic shear [1,2], where enough large gaps can appear. In our approach the large gaps can appear for modes with low poloidal numbers participating in turbulent heat transport according to the formula for the gap width $\delta_{Gap}\sim(m_1*dq/dr)^{-1}$ [3]. These modes arise in plasmas under increased heating when spectrum of turbulent modes shifted to lower numbers due to self-organization in turbulent spectrum. In [3] the dependence of boundary mode numbers for which gaps appear on the density of thermal flux was estimated using experimental data. Modes numbers were estimated in regimes with transport barriers for various heating power in different devices (fig.1). Sharp dependence of modes numbers for which transport barriers appear on heating is seen in the picture. Higher heating leads to excitation of turbulent modes with lower numbers. For these modes the gap between adjacent rational surfaces arises according to the formula (1). In gaps the modes with $m<m_1$ are absent that leads to decreased heat conductivity inside the barrier and ITB formation. Changes in source - sink balance

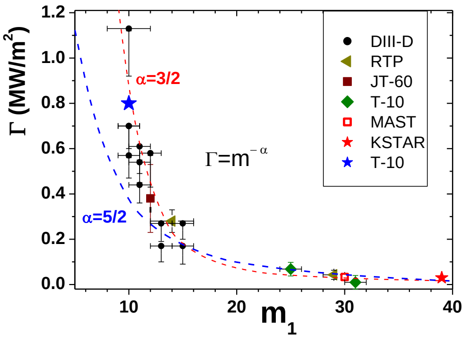

Fig.1

after the barrier formation lead to enhancement of the energy of fluctuating modes with $m<m_1$ on the barrier top, local pressure increase and MHD instabilities development.

In experiments the link between transport barriers and magnetic islands can be observed in plasmas with central ECR heating and sawtooth (ST) oscillations. During temperature ramp

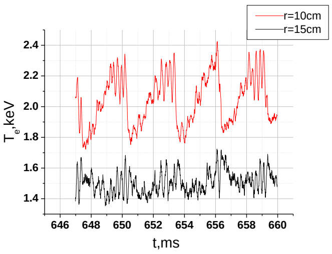

Fig.2

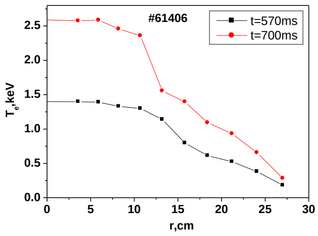

Fig.3

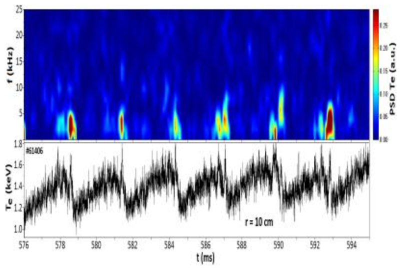

Fig.4

phase in ST oscillation the transport barrier forms near q=1. The discharge parameters are as follows $n_e=3.5*10^{19}$ cm^{-3}, I_p= 220 kA, B=2.4T. In fig.2 and fig.3 time traces and radial distribution of electron temperature measured by electron cyclotron emission (ECE) diagnostics are presented. Radius r= 10 cm corresponds to q=1 and signal at r=13 cm is located outside the inversion radius. The electron temperature profile $T_e(r)$ at t=656 ms corresponds to the maximum of central electron temperature at the end of temperature ramp phase before ST crash. It is seen that the ITB forms in the region of inversion radius. At the end of ramp phase after temperature gradient increasing inside the barrier MHD instabilities develop on the top of the barrier (fig.2). Spectrogram of temperature signals (fig.4) shows that magnetic islands with frequency f_1=2.5 kHz appear on q=1 after beginning of ITB formation. ST period and fluctuations frequency depend on heating power and varies from f_1=2.5 kHz for W=0.5 MW to f_2= 5 kHz for W=1.4MW.

Another case of MHD instabilities development on the top of the barriers has been analysed using the experiments which were pointed to ITB's formation. The scheme of experiments

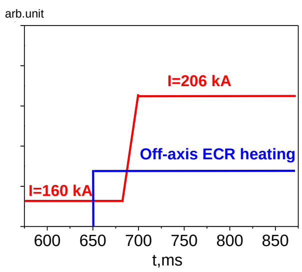

Fig.5

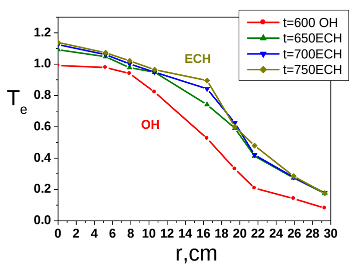

Fig.6

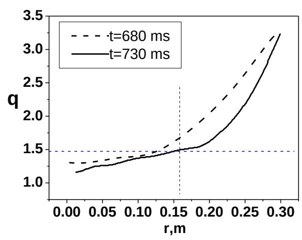

Fig.7

with current ramp-up in ECR heating plasmas is shown in fig.5. Off-axis EC heating was applied to suppress ST activity. In fig.6 the evolution of electron temperature profiles $T_e(r)$ measured by ECE diagnostics shows formation of ITB after current ramp-up phase at t=730 ms. The ITB forms near q=1.5. As can be seen from Fig. 7, development of the barrier is accompanied by flattening of q profile. In present analysis the ECE diagnostics are used to observe both the ITB and MHD instabilities. Time traces of ECE signals show that after ITB formation MHD activity begins to develop on the top of the transport barrier at r=16 cm corresponding to q=1.5 (fig.8). Time dependence of ECE signals reveal complex islands dynamics. It is seen that after series of internal disruptions developed steady-state magnetic islands are observed. Spectral analysis of ECE signal shows that the onset of MHD activity are observed after ITB formation at t=730 ms. On the top of ITB at q=1.5 the modes m/n =3/2 develop. Rotation frequency changes from f=7.5 kHz during t=730-800 ms to f=5 kHz for steady-state magnetic islands which persists up to the end of ECRH phase. Fig.9a and fig.9b present electron temperature and current density profiles before and after ITB formation. In fig.9c q profile and rational surfaces for m = 20, for which the gap corresponds to the width of the barrier, are presented. It is seen that after the barrier formation a bootstrap current rises in the region of maximum pressure gradient in the barrier. Increased bootstrap current causes flattening of q profile, widening of the gap and expansion of the barrier away from the center. In increased gap magnetic islands develop on the magnetic surface q = 1.5. Hereby magnetic islands and the ITB can coexist near the same rational magnetic surface q= 1.5. Magnetic islands develop after the transport barrier formation on the same rational magnetic surface.

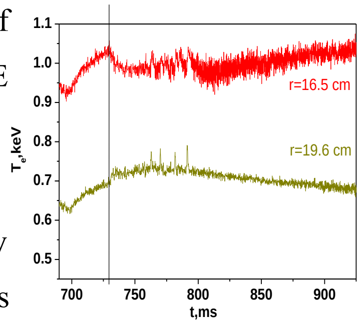

Fig.8

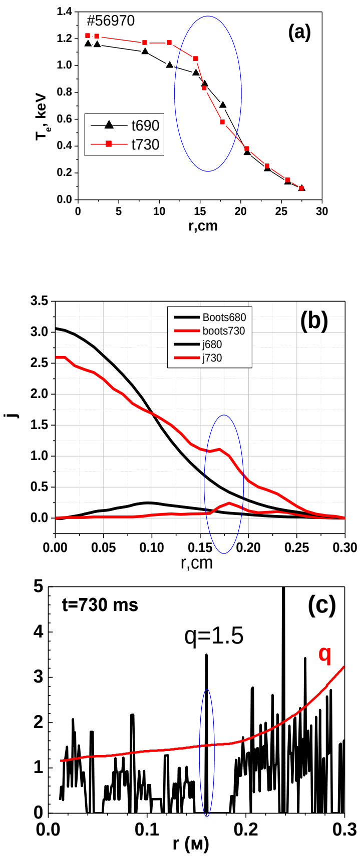

Fig.9

Theoretical analysis shows that magnetic islands can be excited due to mechanisms which are not related with the linear unstable tearing modes. In [5] it was found that the development of small-scale turbulence near rational surface can cause excitation of large-scale MHD instabilities. Nonlinear interaction of electrostatic turbulence and MHD instabilities is important for the processes of self- organization which support anomalous transport.

Evolution of q profile links transport barrier and magnetic islands development. Appearance of magnetic islands can have an inverse effect on transport barrier development. In fig.8 time the dependence of temperature signals at r=16cm and r=19cm shows increasing of the transport barrier after t=800ms when appearance of steady-state magnetic islands is observed. Such feedback loop between magnetic islands and ITB can be responsible for transport barrier enhancement. Changes in local transport properties related with the evolution of magnetic islands may cause appearance of the ExB shearing rate and the associated mechanism of transport barrier development. Non-linear loops between different physical processes are characteristic features of plasma self-organization. Self-organization in the turbulent spectrum under increased heating shifts the modes numbers to lower values, which leads to gaps increase and ITB triggering. Excitation of magnetic islands changes transport properties of plasma and through feedback loop influences the transport barrier. Plasma self-organization provides necessary turbulent flux to plasma column sustentation. From the standpoint of self-organization, the development of MHD instabilities near ITB is a consequence of ITB's formation which violates the persisting pressure profile $P_N(r)$ [4].

Development of ELM's on the top of external transport barriers in H-mode can also be interpreted through the link with the mechanism of transport barriers formation, since both internal and external transport barriers have the same trigger mechanism connected with special properties of q profiles and particularities of self-organization in the turbulent spectrum. Study of physical mechanisms taking into account the link between different processes due to the plasma self-organization can give new insight at physical phenomena in tokamak plasmas.

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