Self-consistent pressure profiles and turbulent modes spectrum in regimes with transport barriers

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Tokamak plasma is known to be a self-organized system. Plasma self-organization is realized in the conservation of the normalized pressure profiles, $p_N(r)$, in regimes with any methods of heating and for a wide class of tokamaks [1, 2]. Pressure profiles are supported by turbulent fluxes, which determine plasma confinement. Heating causes changes of turbulent characteristics and transport properties of plasma increasing heat flux. The study of turbulence features and their changes under additional heating helps to clarify mechanisms of plasma confinement in tokamak. A purpose of this paper is to examine the correlation between turbulent characteristics and turbulent heat fluxes. Structure of turbulence and transport in tokamak plasma are directly connected with the structure of rational magnetic surfaces [3-6]. In [7] it was shown that it is possible to estimate modes numbers in turbulent fluxes in regimes with transport barriers. The method utilized in this work is based on the following. Heat turbulent flux is realized by interaction of turbulent cells, localized at adjacent resonant magnetic surfaces (RMS) by their "overlapping". Transport barriers are formed due to the gaps – regions without RMS which may exist near low number rational surfaces q=m/n when m is less than some value m_1. The gap width can be estimated as $\delta_{gap} \propto 1/(m_1 \cdot dq/dr)$. Here, m_1 is the maximum poloidal number for which gaps exist. For assessments, the width of the transport barrier Δ_{ITB}, can be represented as follows $\Delta_{ITB} = \delta_{GAP} - \Delta_{turbcell}$. Here, $\Delta_{turbcell}$ is the radial size of a turbulent cell which can be estimated as radial correlation length for "broad band" turbulence. The value of $\Delta_{turbcell}$ is about or less than 0.5 cm [2]. Comparing the gap width δ_{gap}, calculated using experimental safety factor profile q(r), with the size of the transport barrier Δ_{ITB} obtained from an experiment, it is possible to estimate m_1 – the minimum number of rational magnetic surface for corresponding turbulent modes in the heat flux. An example of estimating the mode numbers for tokamak MAST [7] is presented in fig.1. The ITB on q=1 in OH regimes has the width of Δ_{ITB} = 2 cm. Corresponding size of the gap δ_{GAP}=3 cm is obtained when maximum number m_1=30 is taken in calculations of the rational surface density. As a result, the barrier exists for the modes with numbers $m_1 \leq 30$.

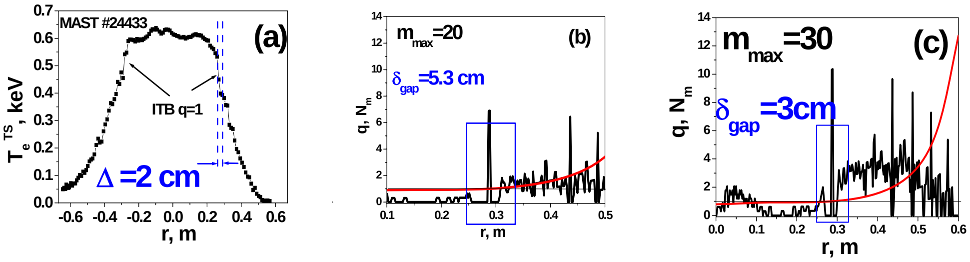

Fig.1 OH regime in MAST a) Te(r); b)and c) q(r) and rational surfaces distributions $N_m(r)$.

To find out a correlation between turbulent heat fluxes and mode numbers the published data in the regimes with transport barriers from different tokamaks have been analyzed [8-14]. The data of temperature and electron density profiles measured by Tomson scattering diagnostics with high spatial resolution were chosen for our analysis that allowed to determine the width of the transport barriers more carefully. For calculations of rational magnetic surfaces the published experimental safety factor profiles have been used. The results for different tokamaks and their different regimes are plotted in fig. 2. Density of

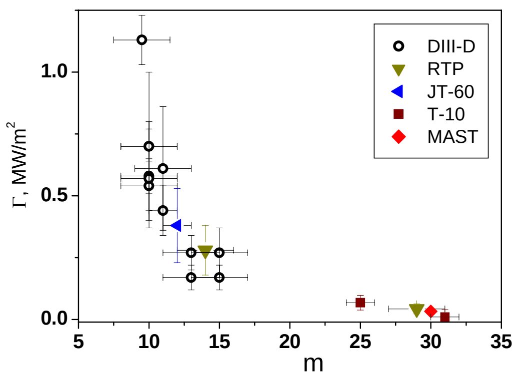

Fig.2. Density of the thermal flux Γ plotted versus modes numbers m_1.

thermal flux $\Gamma=P_{NBI}/S$, where P_{NBI} –neutral beam power, S – a magnetic surface area for different tokamaks, was calculated in the zone of transport barriers. In the experiments under consideration the heating power was varied in the range from 27MW of neutral beam power for JET to 40kW in OH regimes for RTP. It is seen that thermal flux densities Γ and the mode numbers are strict correlated. Obtained empirical dependency $\Gamma(m_1)$ can be approximated as $\Gamma \propto m_1^{-\alpha}$, $3/2 \leq \alpha < 5/2$. It is seen from dependency $\Gamma(m_1)$ that the higher thermal fluxes in tokamak plasma is associated with the modes of lower numbers. But as it was shown earlier the modes of low numbers have increased gaps between RMF that result in transport barriers formation for these modes. Inside the barrier turbulent flux is realized by modes of higher numbers for which there are no gaps. Low fluxes connected with these high number modes correspond to better confinement inside the barriers. So the spectrum of turbulent modes in plasma can characterise plasma possibility to heat transfer.

In regimes with high heating power and a flat q profile many gaps may appear for low turbulent mode numbers. This case corresponds to “Advance tokamak” regimes [9]. Fig.3 (a) shows the experimental q(r) and rational surfaces distribution calculated for m_l =10 for DIII-D pulse with enhanced confinement [9]. Many gaps along the radius are seen in the picture. They correspond to a chain of barriers almost merging with each other giving enhanced confinement regime.

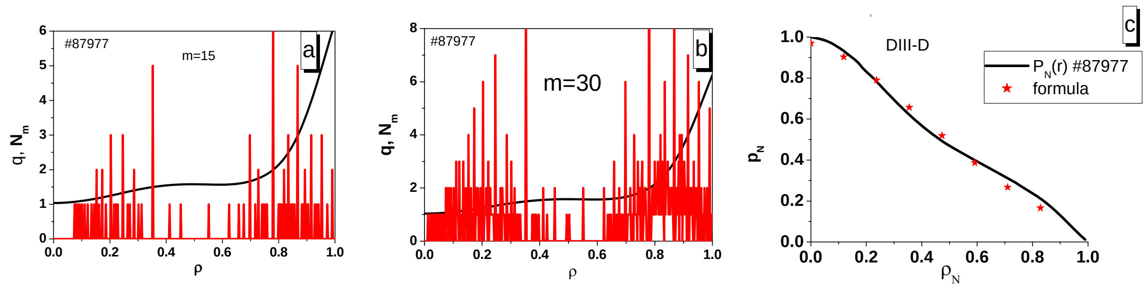

Fig.3. “Advanced tokamak” regimes in DIII-D a) and b) q(r) and rational surfaces distribution $N_m(r)$ for m_1 =15 and m_1 =30. c) normalized pressure profile P_N (r).

Calculations show that for m_l=30 the gaps become smaller (fig.3b) and for m_l=60 there are no gaps for given experimental q(r). One can conclude that the modes with numbers m > (30-50) are responsible for low transport in the region of ITB’s.

The existence of a wide region occupied by the barriers allows to analyze the plasma pressure profile inside the ITB’s zone. In fig.3 (c) the normalized pressure profile $P_N(\rho)$ and the universal pressure profile are plotted. To build $P_N(\rho)$ the experimental pressure profile for #87977 given in [9] has been used. Here, $P_N=P(r)/P_0$, P_0 – the value of the central pressure, $\rho = r/(IR/kB)^{1/2}$, I and B are the plasma current and toroidal magnetic field, R is the plasma major radius and k is a parameter of plasma elongation. Stars in the picture correspond to an approximating formula for the universal pressure profile $P(\rho) = (1- \rho^{1.5})^3$ (4). It is seen that the normalized pressure profile in “advanced tokamak” regimes is the same as that obtained in regular tokamak regimes without transport barriers [1]. In fig.4 the results for experimental data in “advanced tokamak” regimes in JET [13] are presented. Good agreement between experimental $p_N(\rho)$ and universal formula (4) is obtained for the JET tokamak as well. Calculations of rational surfaces for the published experimental q(r) in the pulse under consideration show that under high heating power (W=23MW) many gaps between RMS are seen in the zone of enhanced confinement for m_l=10 (fig.4 (b)).

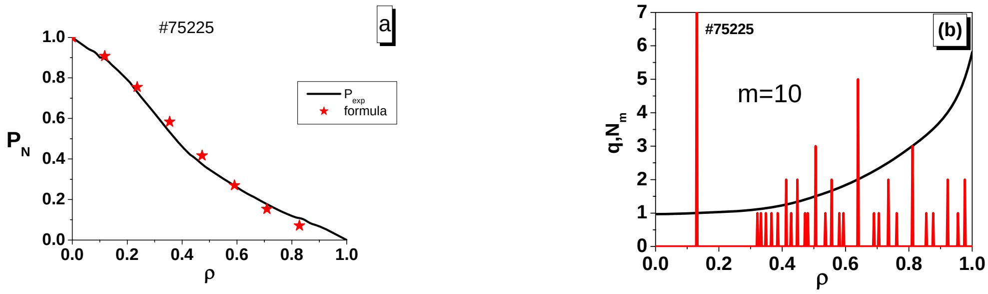

Fig.4 “Advanced tokamak” regimes in JET a)Te(r); b)q(r), the rational surfaces distribution $N_m(r)$ for m_l=10

From obtained results one can conclude that gaps increasing and formation of the barriers under additional heating is a mechanism of transport reduction to support universal pressure profile. Confinement in self-organized plasma depends on the heating power and the range of turbulent modes participating in transport.

Analysis of experimental profiles in regimes with transport barriers has allowed to study the mechanisms of self-organization in tokamak plasma. These mechanisms are realized through the creation of turbulent structures connected with rational magnetic surfaces and distributed in plasma in such a way to support turbulent fluxes necessary for the formation of the universal self-consistent pressure profile. The universal formula for normalized pressure profile can be used in analysis of experimental data and regimes modeling.

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