Main features of turbulent flux responsible for plasma self-organization and energy confinement.

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From the self-consistent pressure profile paradigm [1] it follows that any external impacts lead to appearance of turbulent fluxes trying to restore the pressure profile shape. The aim of the work is to find some characteristics of the turbulent energy flux which regulates self-consistent pressure profile and determines plasma confinement in regimes with internal transport barriers (ITB). It is known [2, 3, 4] that ITB occurs in the vicinity of the low number rational surfaces (q=m/n=1; 1.5; 2 …) in so called gaps where rational surfaces with modes numbers less than some definite upper number M are absent. In gaps turbulent energy flux associated with these modes is substantially diminished. To estimate poloidal number **M** of the turbulent modes from an experiment we compare experimental ITB radial width $\boldsymbol{\Delta_{ITB}}$ with a gap value, $\delta_{gap,}$ which can be deduced from the calculations of radial rational surfaces distribution $N_m(r)$. The width of a gap depends on q(r) and upper poloidal number $\boldsymbol{m_{max}}$ used in calculations $\delta_{Gap} \propto q/(\boldsymbol{m_{max}} * dq/dr)$. Here q(r) is taken from an experiment and $\boldsymbol{m_{max}}$ =**M**. The ITB width Δ_{ITB} and δ_{GAP} are linked by the relation $\Delta_{ITB} = \delta_{GAP} - \Delta_{turb\ cell}$. The last term, which is the characteristic of the radial dimension of turbulent cells is the most uncertain, its typical value in T-10 is about 1cm [5]. So we estimate the upper value of M.

In our study the experimental data for regimes with ITB's from different machines have been used [6 – 10]. In fig.1 the MAST results for OH regime [6] are presented. For this case experimental width of the ITB Δ_{ITB}=2cm. For $\boldsymbol{m_{max}}$=50 estimated gap δ_{GAP}=1,5cm; and for $\boldsymbol{m_{max}}$=20 δ_{GAP}=5.3cm. The most probable poloidal number for the given Δ_{ITB} as we suppose is $\boldsymbol{m_{max}}$ =30 with the gap between adjacent resonant surfaces δ_{GAP}=3cm.

Turning now to the RTP tokamak, fig.2 shows that for OH regimes [7] $\boldsymbol{m_{max}}$ =30, corresponding to the ITB on q=1 is obtained. One can see that for these two very different tokamaks (see table) in OH regimes the core turbulent flux is carried by modes with approximately the same poloidal numbers. In both cases under $\boldsymbol{m_{max}}$ =30 in the calculations of rational surfaces distribution the gap near q=2 exists without any ITB's there. Hence in the plasma volume turbulent modes numbers increase to the outer region, here $\boldsymbol{m_{max}}$ > 40. The results for the powerful on-axis

ECRH regime in RTP (0.4MW, a =16.4 cm) [8] are presented in fig.3. A wide ITB (Δ_{ITB} =1 cm) is formed at q=1 in this case in spite of dq/dr increase in the plasma core due to more peaked compared to OH regime current density profile. Calculations show that $\boldsymbol{m_{max}}$ is about 10 in this case. The heat transport through the q=1 surface increases by a factor of 20 in comparison with OH regimes (20 kW inside this zone), but estimated $\boldsymbol{m_{max}}$ is decreased 3 times only. So for a strong heat flux increase the decrease of the poloidal number of the turbulence occurs in a less degree. The second important result – the appearance of a wide ITB in ECRH regime shows that the gap size increases more strongly for smaller resonant M than the width of the turbulent cells. Consequently the ITB is triggered not only by q(r) profile control, but also due to the plasma self-organization in response to external heat impacts trying to distort the self-consistent pressure profile. For off-axis ECRH we expect M increase in the central zone due to a decrease of turbulent heat flux there and M decrease in the outer region. Really in RTP experiment [8] (see the table) M increases from $\boldsymbol{m_{max}}$ =30 (OH) up to $\boldsymbol{m_{max}}$ =60 inside q=3. In contrast, after off-axis ECRH switch-off the heat flux in the central zone increases. As a consequence $\boldsymbol{m_{max}}$ decreases in the central region from 60 to 20 (see the table) and ITB occurs due to the gap appearance at q=2 surface under low $\boldsymbol{m_{max}}$ number (fig.4). Central pressure increases nearly twice in this case. As a result of the experimental data analysis the dependence of specific heat flux $\Delta\Gamma/\Delta m$ versus m can be schematically shown as in fig.5. Two regimes with substantially different heat flux values are shown. In OH regime heat flux which regulates a self-consistent pressure profile, $p_N(r)$, is not high and associated with modes **M**≅30 in the plasma core (fig.5 curve1). When external impacts are strong, the regulating fluxes are realized by modes with smaller **M**≅10 (fig.5 curve 2). Modes with higher **M** numbers are also present in both cases but they carry less turbulent fluxes. For low **M** modes the gaps enough for ITB formation can appear under the same q(r). Inside the gap region the heat flux can be transported by higher **M** modes, for which gaps are absent. But higher **M** modes can carry only smaller energy flux and necessary power can be transported at enhanced ∇p and increased confinement.

At the plasma outer region a strong external impact, i.e. edge cooling, exists. Together with powerful plasma heating this factor may distort $p_N(r)$ at the plasma edge. As a result increased heat flux is carried by diminished **M** numbers modes for which a wide gap between resonant surfaces can appear and transport barrier may be formed. In the process of transport barrier formation the bootstrap current makes the gap wider. This may be the underlying mechanism of H mode formation. H mode regime in TEXTOR [9] is presented in fig. 6. One can see a wide gap δ_{gap}=2cm at the plasma edge in the region of the transport barrier location (Δ=2.5cm).

Calculated $\boldsymbol{m_{max}}$ is about 20 for this case. In fig.7 a DIII-D pulse with H-mode is shown [10]. The transport barrier position coincides with the q(r) flattening, Δ =2cm and for $\boldsymbol{m_{max}}$ =30 δ_{gap}=4.4cm.

Conclusions

1. The suggested method of the results analysis appears to be productive. Obtained results may help to clarify the physics of turbulent transport and ITBs triggering.

2. The following picture emerges: a) the self-consistent pressure profile, $p_N(r)$, is the most stable configuration with the best confinement for given conditions. b) External impacts (heating, cooling and so on) trying to distort $p_N(r)$, change the equilibrium currents distribution and so excite some MHD instability. c) Small deformation leads to small-scale turbulence, with high mode number M, which transports the flux necessary for the pressure profile repair. d) For more strong external impact, more large turbulent scale is needed, so lower modes numbers are responsible for the pressure profile regulation.

3. It is probable that H mode is a result of the gap formation due to the enhanced heat flux transported by low M turbulence.

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References.

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tokamak	Parameters	heating	region	m	references
MAST	MAST R=0.8m; a=0.6m; k=2	OH	Inside q=1	30	[6]
RTP	RTP R=0.72m , a=0.164m; k=1	OH	Inside q=1	30	[7]
RTP		OH	Inside q=2	>40	[7]
RTP		On-axis ECRH 0.4MW	Inside q=1	10	[8]
RTP		Off-axis ECRH	Inside q=3	60	[8]
RTP		Off-axis ECRH switch off	Inside q=2	20	[8]
TEXTOR	R=1.72m; a=0.447m;k=1 B=1.3T; Ip=235kA	P_{NBI} 1.6 MW	Plasma edge H-mode	20	[9]
DIII-D	R_m=1.75m; a_m= 0.6m; k=1.76 I_p=1.22 MA B=2T	P_{NBI} =2.9 MW	Plasma edge H-mode	20–30	[10]

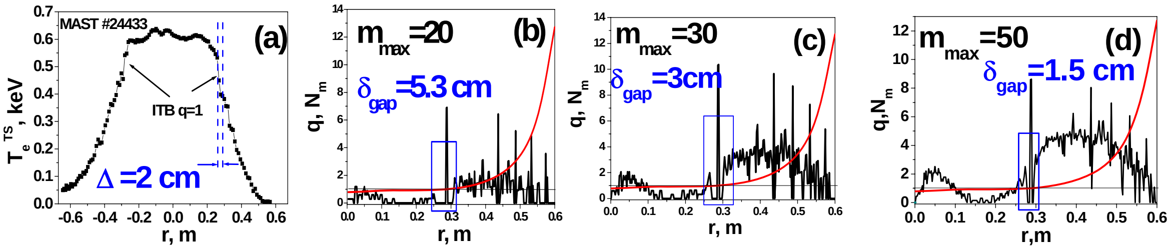

Fig.1. MAST. OH regime, a) Te(r); b),c),d) q(r) and rational surfaces distribution $N_m(r)$ for different $\boldsymbol{m_{max}}$

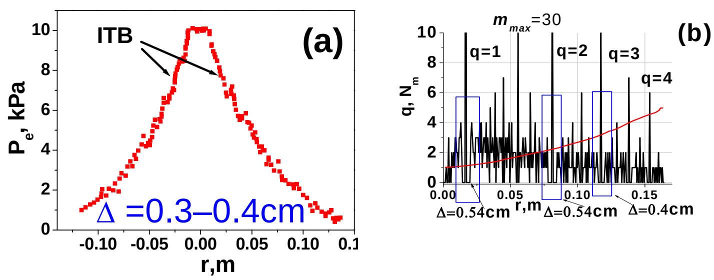

Fig.2. RTP. OH regime, a) Te(r); b) q(r) and $N_m(r)$ for $\boldsymbol{m_{max}}$=30.

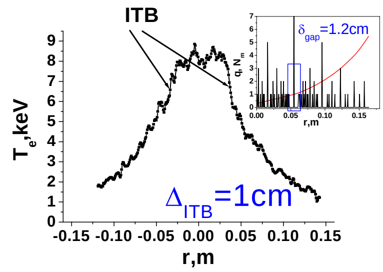

Fig.3. RTP. $T_e(r)$- strong ITB at q=1 in on-axis ECRH; in enclosure - q(r) and $N_m(r)$ for $\boldsymbol{m_{max}}$=10.

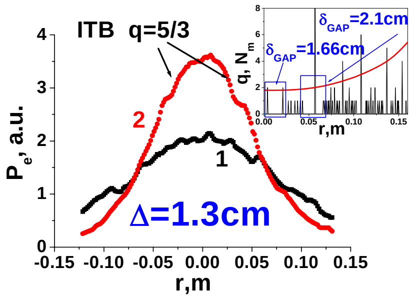

Fig.4. RTP. P(r) before (1) and after (2) ECRH switch-off in OH regime; in the enclosure -q(r) and $N_m(r)$ for $\boldsymbol{m_{max}}$=20.

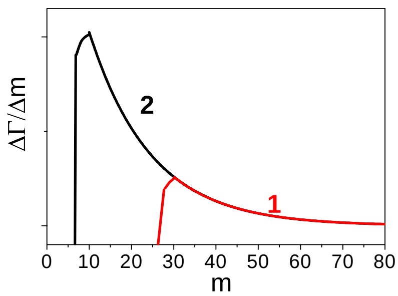

Fig. 5. The scheme of the dependence of specific turbulent thermal flux on m.

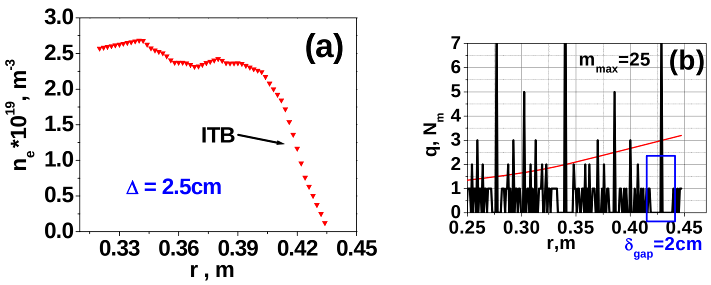

Fig.6. TEXTOR. a) the edge electron density profile; b) q(r) and $N_m(r)$ in H-mode regime.

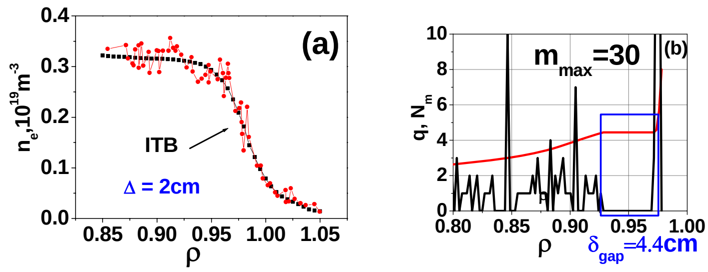

Fig.7. DIII-D. a) the edge electron density profile; b) q(r) and $N_m(r)$ in H- mode regime.