ANOTHER LOOK AT TOKAMAK PLASMA PHYSICS

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This great scientists, who founded the basis of plasma physic don’t work with us more, but we all the time use the ideas given us by them
In the eighties - nineties a number of new wonderful effects were found and did not explained:


2. Different values of thermal conductivity coefficients found from power balance analysis and from heat/cold pulse propagation analysis (including the sawtooth crush propagation).

3. Very fast propagation of thermo-diffusivity changes produced either by edge plasma perturbation or by pellet injection – *non local dependence of plasma transport coefficients on plasma parameters*.

4. Particle and thermal pinch effect.
In the Arthimovich’s time the word “turbulence” frighten us as a sword of Damocles.

To-day we know that plasmas are always turbulent! And this is not bad – **due to the turbulence existence we have a well organized substance!**

In Nature each substance, which has some degree of freedom is **self-organized**. It tries to have the best from potential energy point of view configuration. This relates, for example, to atmosphere, to molecular and biology systems. This relates to plasmas. *(Formation of structures in a dissipative medium is called synergism it is a new interesting branch of science)*

**Beside the usual degrees of freedom turbulent plasmas has a very important possibility to change its local transport coefficients, changing the turbulence flux at different radii.*
B.B. Kadomtsev wrote in the beginning of nineties:

“Tokamak plasma transport is viewed as a phenomenon of self-organization. Nonlinear relation between fluxes and gradients provides a variety of confinement modes and profile resilience”

The temperature profile consistency or resilience (or stiffness) experimentalists disclose in some conditions as soon as good temperature profiles measurements became possible.

But little later it was shown that the pressure profile conservation exists always.

Temperature profile resilience is a particular case, when the density profile is also conserved
Self-consistent normalized pressure profile

There are two main fundamental phenomena, defining the confinement in tokamak plasmas:

(i) the self-organization of the plasma pressure profile and
(ii) the occurrence of internal and edge transport barriers

normalized pressure: \( p_N(r) = \frac{p(r, t)}{p_0(t)} \) is independent on plasma parameters, but \( r \), or \( \frac{p'(r, t)}{p(r, t)} = f(r) \)
The following characteristics of pressure profile conservation have been observed:

1. $p_N(r)$ is independent on plasma density and so on the dominant type of plasma drift wave instability, because for different density diapason different fluctuation spectra are registered under the same $p_N(r)$. 
2. $p_N(r)$ is independent on type and radial profile of auxiliary plasma heating power

\[ \rho = r/(IpR/\kappa B)^{1/2} \]

For comparison the T-10 Ohmic shot is shown.

#106221 $I_p = 240$ kA, $B = 2.5$T, $P_{NBI} = 1.02$MW, $P_{ICRH} = 1.425$MW;

#106227 $I_p = 240$ kA, $B = 2.5$T, $P_{NBI} = 1.05$MW

off-axis ECRH, $P_{ECRH} = 0.8$MW.
3. The scaling

Normalization of current plasma radius to the radius of any magnetic surface outside the plasma

\[ \rho = r / (I_p R / k_B)^{1/2} , \]

allows us to describe the self-consistent pressure profile for tokamaks with different geometries and \( q_{edge} \) values.
For small round RTP and for large elongated JET we have the same normalized pressure profiles.
Haw $p_N(r)$ depend on aspect ratio, $A$?

MAST, $A=1.5$, and T-10, $A=5$, have the same profiles.
4. $p_N(r)$ is independent on longitudinal $j_\parallel(r)$

T-10, experiments with different $j_\parallel(r)$ distribution
Experiments with rapid current ramp up at the stationary tokamak process with off axis heating suppressing the sawteeth.

The $\Delta_{gor}$ and $p_N(r)$ are changed in accordance with formulas $\Delta_{gor} \sim \beta_p \sim 1/I^2$ and $\rho = r/(I_p R/kB)^{1/2}$ practically synchronously with the current value change, for not monotone current density distribution, long before $\Delta j_{\parallel}$ penetrate into the plasma core.

Only equilibrium realizes so quick!
5. The restoration time for the pressure profile
\( \tau_c < 0.1 \tau_E \) - energy confinement time

At the ECR heating start measured \( p_N \) conserves in time 10 times shorter (0.25ms) than the energy confinement one (3ms).
It is useful to mention that self-consistent pressure profile exist not only in tokamak plasmas, but in stellarator ones too.

\[ p_N(\rho) \] for CHS, ATF: W7-AS: and TJ-II for different regimes. Experiments were radially normalized to the actual plasma size. Black curve is an H-mode in TJ-II.
What is the mechanism of $p_N(r)$ conservation?

To answer this question let us see, when this profile is not realized.

1. $\triangledown p_N(r)$ exceeds that predicted by self-consistent profile in the ITB regions.

2. after the sawtooth crush the flattened pressure profile does not restore inside $q=1$ area as rapidly as in usual cases, but only after the reestablishment of magnetic surface structure, which takes the time between crashes.

3. When external impacts are too strong, we see more steep gradient than $p_N(r)$. 
1. In some theoretical papers it was argued that the main plasma instabilities develop in the vicinity of rational surfaces and form turbulent cells.

Cells of the various $m, n$ modes may overlap, and this may be the reason for the anomalous transport.

Experiments confirm that electron ITBs form in the rational surfaces “gaps”

This was excellently shown in experiments at JET and DIII-D

Self-consistent presser profile regulation does not exist in the “gap”.

Correlation Alfvén cascade - ITB triggering event.

1- When Alfvén cascade and triggering event are both observed, they occur at the same time within 0.2s.

2- This indicates that the triggering event is related to \( q_{\min} \) reaching a rational surface.

3- This correlation is observed for a large variety of plasma conditions:

\[ 1.5 < I_p < 2.8 \text{ MA} \]
\[ 2.45 < B_T < 3.4 \text{ T} \]
\[ 3 < P_{\text{TOT}} < 17 \text{ MW} \]
Mechanism of $p_N(r)$ conservation

To answer this question let us see, when this profile is not realized.

1. $\nabla p_N(r)$ exceeds that predicted by self-consistent profile in the ITB regions.

2. after the sawtooth crush the flattened pressure profile does not restore inside $q=1$ area as rapidly as in usual cases, but only after the reestablishment of magnetic surface structure, which takes the time between crashes

3. When external impacts are too strong, we see more steep gradient than $p_N(r)$
During the sawtooth crush magnetic topology is destructed.

Absence of self-consistent profile in this case means that self-consistent mechanism needs in rational surfaces existence and in overlapping of turbulent cells accumulated on them.
It is a rude scheme only. The idea of this was suggested by:


Particularly B.B. Kadomtsev suggested that chains of magnetic islands appears in topology and, when these chains touch each other, a stochastization of magnetic field lines takes place. “If the local gradients of the temperature and density exceed their canonical values a tendency to stochastization prevails and additional transport fluxes are produced. In contrast, lower than canonical profile relative gradients hinder magnetic fluctuations and diminish transport flux.”

B.B. Kadomtsev, 1996

Similar mechanism of transversal energy flux was suggested by M. Rosenbluth and A. Rachester in 1978, irrelatively of plasma self-organization.
Recent model of V.P. Pastukhov and N.V. Chudin

The model is based on direct computer simulations of nonlinear vortex-like plasma convection self-consistently excited by a pressure-driven instability. The simulations have shown formation of stochastic (turbulent) convective cells, which generate a non-diffusive cross-field particle and heat fluxes and maintain the plasma near a marginally-stable turbulent relaxed state, corresponding to uniform radial profile of plasma entropy.

\[ S = p \ U^r = \text{const} \quad (U = \oint dl / B_p) \]

Model allows to simulate regimes with fast transient processes, such as heat pulse propagation.
Mechanism of $p_N(r)$ conservation

To answer this question let us see, when this profile is not realized.

1. $\nabla p_N(r)$ exceeds that predicted by self-consistent profile in the ITB regions.

2. After the sawtooth crush the flattened pressure profile does not restore inside $q=1$ area as rapidly as in usual cases, but only after the reestablishment of magnetic surface structure, which takes the time between crashes.

3. When external impacts are too strong, we see more steep gradient than $p_N(r)$. 
External impacts, like edge conditions, auxiliary heating / cooling and so on hinder plasma to mountain its self-consistent profile and force it to increase transport fluxes. But, when this impacts are too strong, the small scale turbulence ($\Delta \ll a$, maximal plasma radius) could not supply the flux high enough and $p_N(r)$ deviates from the canonical one.

Plasma begin to use MHD macroscopic instabilities, ($m=2$ mode(in given case))
Diviation from the self-consistent pressure profile takes place in a very important zone of maximal gradients.

If this process will lead to a “small disruption” (internal disruption with $q=2$) the magnetic topology will be destroyed, like in the case of sawtooth disruption with $q=1$, but in a large area and plasma will lose the possibility for self-organization at all.

This will lead to a total lose of low modes number MHD stability and to major disruption.

So we can conclude that plasma needs in self-consistent pressure profile for its macroscopic low modes number MHD stability.
A fuller picture of tokamak plasma physics is beginning to emerge in the frames of made hypothesis.

The tokamak plasma is a well organized turbulent system, which regulates the pressure profile in a form necessary for the low modes number MHD stability.

Its self-organization is fulfilled due to existence in plasma specific magnetic topology – structure of rational magnetic surfaces. The turbulent flaxes are regulated as a result of overlapping of the turbulent cells accumulated at rational surfaces.
The fluxes increase if by external impacts the local pressure gradient exceeds that predicted by self-consistent pressure profile and vice versa.

The possibility of steeper $\nabla p_N$ appearance exists only in districts, where contact between the cells is broken (near the rational surfaces with low numbers $m$ and $n$) and turbulent activity is low.

The position and wideness of ITB depends on the longitudinal current density distribution $j_\parallel (r)$ in contrast with $p_N(r)$, which independent on it
Strong distortions of $p_N(r)$, which usually connects with the bad edge conditions, leads to $p_N(r)$ modification, shortage of the small scale turbulent transport flax and than loose of the macroscopic MHD stability, which is too rude for $p_N(r)$ restoration.

Due to internal $m=2$ disruption plasma lose its magnetic topology and possibility to self-organization. This leads to a total disruption.

MHD character of the process determine short time of $p_N(r)$ restoration.
Consequence I :

Being in frames of this hypothesis we can explain mentioned above plasma phenomena.

1. Many tokamak operating modes links to different variants of ITB formation due to different $q(r)$ profiles and so “gap” widths near rational surfaces.

2. The speed of heat/cold wave propagation bounds with the impossibility to distort $p_N(r)$. Stronger the distortion – higher the rapid turbulent flux change in the distortion region, – higher the difference between real heat wave propagation speed and that calculated from the energy balance.
3. As radial distribution of transport coefficients is determined by $p_N(r)$ conservation they are not a function of local parameters. So changing parameter profiles at plasma periphery (cooling, for example), we practically simultaneously change the turbulent fluxes distribution. This may lead to new $T_e(r)$, redistribution of $j_{\parallel}(r)$, and ITB formation/degradation. Note that for q(r) changes near the rational surface, which can lead to the ITB quality change, we need in q(r) redistribution in the vicinity of ITB only. This does not take a long time.

4. Particle and thermal pinches are used by plasma for $p_N(r)$ regulation. The mechanisms we still do not know well enough,
Consequence II.

1. The diffusion equation cannot be used in transient tokamak processes, since the transport fluxes (transport coefficients) can be rapidly changed by dozens of times.

2. We must very guardedly use scalings especially for far extrapolation, because plasma behavior is ruled at least by two processes with different parameter dependence.

3. We don’t need to make efforts for stabilization of any instability (including NTM). We need to help plasma to keep $p_N(r)$. 
4. The best confinement is obtained in the OH case, where the power deposition profile has the possibility to redistribute itself in the best way.

\[ P_{OH}(r, t) \sim T_e^{3/2}; \quad p = n_e T_e. \]

If \( n_e(r, t)/n_e(0, t) = [T_e(r, t)/T_e(0, t)]^{1/2} \), like it always take place in OH, the \( P_{OH}(r) \) and \( p(r) \) profiles will be similar, and \( P_{OH} \) increase will not distort the pressure profile.

For reactor \( W_\alpha(r) \sim p^2(r) \). We may expect the confinement degradation, but we have the possibility to generate ITB and to improve this conditions.
Problems

♦ We speak about the normalized pressure profile only. The normalization coefficient may be different for different cases. Probably this coefficient depends on the mechanism, which plasma uses for its self-organization.

♦♦ We see that self-consistent pressure profile is needed for the macroscopic MHD stability, but we don’t know, why namely this pressure profile valid the MHD stability?
In 1982 at the IAEA conference in the conclusion paper Harold Furth said:

“...Relative to the perceived reactor requirements, expectations as to what is likely to be achievable seem to have executed a damped oscillation: Expectations were positive at the outset, dropped into the negative range during the 1960s, became positive again during the early tokamak era of the 1970s, and dropped to slightly negative values during the rise in perceived reactor requirements that has taken place in the last few years. (beginning of 80s)

I believe that if we will deeply understand the tokamak plasma physics we will have the possibility to rule plasma processes, and this curve will be monotonically growing and optimistic.
We can’t have help of our wise teachers, who have already passed, but I believe that in this hall there are some clear minds that can look at plasma physic from not usual side and find answers for our difficult questions.