Committee 5
Non-linear Structures in Natural Science and Economics

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Non-linear Dissipative Structures in Hot Plasma

Ksenia A. Razumora
Head of Laboratory
Russian Research Center
Kurchatov Institute
Moscow, Russia

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K.A.Razumova

Abstract

A lot of different kinds of instabilities may be developed in high temperature plasma located in a strong toroidal magnetic field (tokamak plasma). Non linear effects in the instability development result in plasma self-organization. Such plasma has a geometrically complicated configuration, consisting of the magnetic surfaces imbedded into each other and split into islands with various characteristic numbers of helical twisting. The self-consistency of the processes results in that the transport coefficients in plasma do not depend on the local parameters only, being a function of the hole plasma configuration and of the forces affecting it. Disrupting the bonds between separate magnetic surfaces, filled with islands, one can produce the zones of reduced transport in the plasma, i.e. “internal thermal barriers”, allowing one to increase essentially the plasma temperature and density.

1. INTRODUCTION

High temperature plasma in magnetic field is widely represented in Space, e.g. on the Sun and on other stars, but it cannot be found in nature on Earth. For studying such plasma the scientists are forced to produce it artificially. In particular, the plasma produced for realizing the controlled fusion reactor is used. Among such facilities the “tokamak” is the most popular one. There the plasma torn with a current is located in a toroidal magnetic field. The temperatures of ions and electrons may attain 10-40 keV in such facilities. Analogues configurations –but with lower particle temperature - may be seen in a Solar corona.

This paper will concern to the information received in plasmas of such configuration.

2. MHD INSTABILITIES

The plasma, even located in a strong magnetic field, is a very movable substance. It reacts to any force by a drive of some instability, which leads to a change of plasma transport coefficients, depending on an instability development level. The large-scale magnetohydrodinamic (MHD) instabilities are the most essential ones. Since a current flow in tokamak along the externally created toroidal magnetic field, the total magnetic field configuration has helical structure, and its strength depends on current density distribution profile. The level of the magnetic force lines twisting is characterized by the value of $q=B_t r/B_p R$, where B_t , and B_p are the toroidal and the poloidal magnetic field strengths, R is the major radius of the torus, r is the current minor plasma radius. At some plasma radii, the field lines are closed to itself after m path tracings. They are able also to do n torn more around the toroidal axis. The magnetic surfaces produced by such field lines are called rational ones. They are unstable to the current twisting along the magnetic field lines, and to the production of the "islands" with enhanced current density. This results in the corresponding magnetic field distribution distortion. The islands can increase in size until non-linear processes will not stop their growth. So the plasma acquires the rather hard, well pronounced structure which can stationary exist.

The plasma, pierced with "snakes" with different m and n values, rotates, at the same time, in the poloidal and toroidal directions with various velocities at different radii. Thus the MHD instabilities results in the production of the new stable configuration which affects, in its own way, the plasma confinement. In Fig1,[1] the temporal evolution of such picture is presented. The image of glowing plasma was reflected upon fast-rotating film. One can see large, probably $m=3$, structure and more fine structure in plasma edge. Both structures rotate in opposite direction. In this picture it is impossible to see islands with $m=1$ and $m=2$, since the temperature in plasma core. is too high and plasma does not radiate in visible range. They can be seen in X-ray radiation range only.

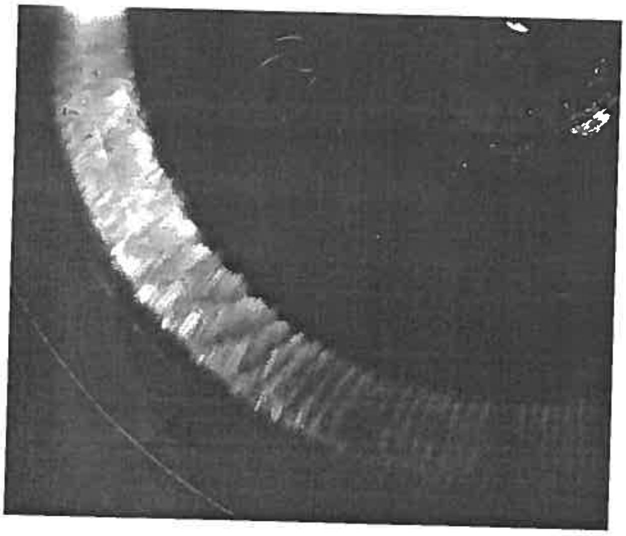

Fig.1. TM-3 tokamak. The temporal behavior of the image of the glowing plasma. The slit, looking at the plasma, was reflected upon the rotating film. The tine pusses from up left to down right.

The electron temperature profile measurements, made with a very good space resolution (Δr=0.3cm for r_{max}=20cm) have shown that the central part of plasma, beside of the resonance islands, is filled with thin threads of an inhomogeneous plasmas, so called, filaments,[2].

The island size depends on the magnetic field lines twisting rate change along the radius, in the island region, dq/dr. The higher is dq/dr, the smaller is the transversal size of the island. The adjacent islands can be linked at their edges, and, interacting, can give birth to more complicated structures with high m and n, or can produce the zone with completely destroyed magnetic surfaces. This is very essential for the rate of heat and particle transport across the magnetic field. In ideal totally stable plasma under strong magnetic field the heat and particles almost cannot move across the magnetic field because of a small Larmor radius in comparison with particles free pass between collisions (frozen plasma). Meanwhile the heat in the magnetic islands freely flows from the internal island side to the external one, and turbulization between the islands allows the heat (and particles) to reach the next island and so to convey the heat to the wall of containing plasma chamber.

If q<1 in a small central region, the angle between the magnetic force lines inside and outside of the surface S with q=1 and that on the surface S will have different sign. Following B.B.Kadomtsev [3] let us divide the magnetic field into two components: one is in accordance with q(r)= const =1, another, B^*, is a poloidal field which provide a declination q from the unity: q<1 inside S, and q>1 outside it. Under the infinite electro-conductivity that configuration permit some displacement of the central hot plasma part to S, which will be limited by increasing magnetic field strength in the side of displacement. But if the conductivity is finite the current, which generates this field, will decrease and the rapid process of the magnetic field lines reconnection will increase q(0) up to1 and push out of the surface S the central heat and poloidal magnetic flux (Fig2). Then $T_e(0)$ will increase again, and q(0) will go down. Temporal behavior of $T_e(0)$ in this case looks like the teeth of saw (Fig3a).

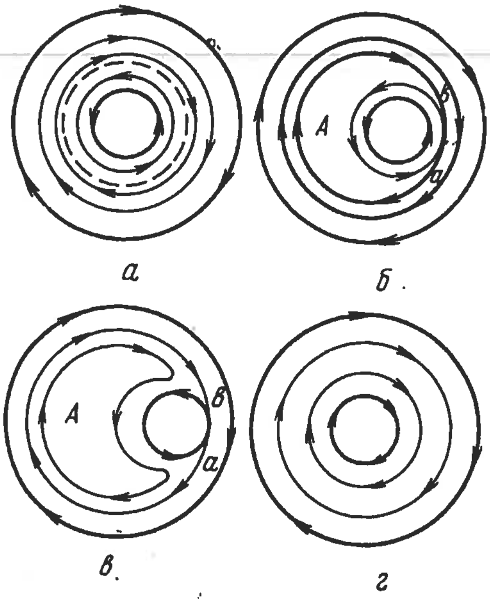

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Fig.2. The behavior of the poloidal field B^* in plasma cross section at different moments during internal disruption formation. At the beginning B^* has different direction inside and outside the surface q=1. After the process of magnetic field lines reconnection it has the same sign in the entire plasma area,

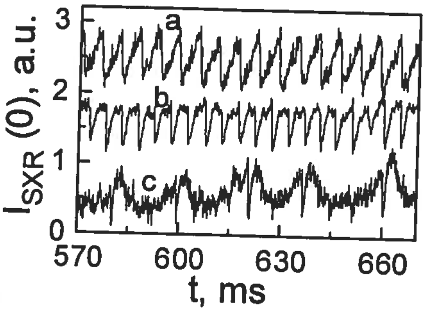

Fig 3. The temporal behavior of the central SXR intensity.
a) For usual Ohmic heating regime.
b) and c) For the regimes, when q_{min} *increase and approaches to unity (c).*

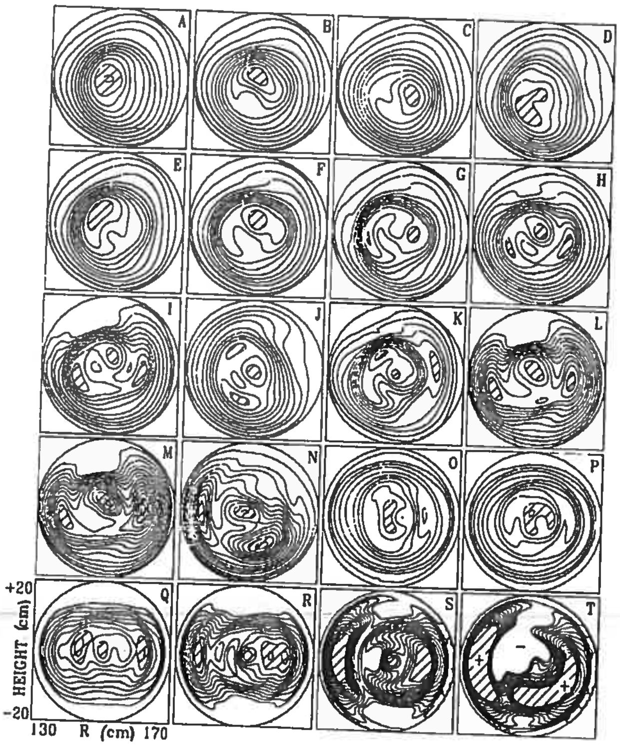

Fig.4. T-10 tokamak. The result of the tomografic reconstruction of the SXR profiles for three angles of registration. The successive instance during the disruption development begins at the top left and goes in alphabet order. The time resolution is 10mks. The time between pictures is 60mks.

`If the $q<1$ zone is large the process of the magnetic lines reconnection may include also another islands with $m=2$, and may be with higher m. Then the current and heat release from the plasma core can result in the complete plasma disruption. In Fig 4, [4] one can see the picture of the equal X-ray radiation intensity levels. It was received as a result of the tomographic reconstruction of the SXR profiles for three angles of registration at successive instants during the disruption development. One can see a strong deformation of plasma structure with blowout of hot central part to the periphery of plasma at the end.

3. PROFILE CONSISTENCY

An uncountable amount of various plasma instabilities has been theoretically predicted. Though, in practice, only the most strong of them are obviously seen in plasma, plasma always has in its arsenal something, which it can use in given conditions. It is clear that each instability tends, using the energy from the parameter gradient exciting it, to change it to the level necessary for the stabilization. Thus, the plasma in ideal variant should stabilize itself, producing the best profiles for a complete stability. However, it never happens, since we prevent plasma to have parameter profiles, it needs, introducing external forces. First of all, it is boundary conditions, which spoil an ideal profile at a definite radius. It makes steeper gradients of the plasma parameters: electron and ion temperature T_e and T_i, electron density n_e and etc. These gradients are sources of the continual power supply for the instability, and, as a result, for the enhanced transport coefficients.

If the destabilizing factors are more or less standard for various takamaks, we shell be right to expect the emergence of the same type parameter profiles for various facilities. It is illustrated in Fig5 [5]. It has been shown that an attempt to increase the energy in the central part of plasma only results in a heat conduction rise under conservation of the same profile, in spite of a rise in the central temperature. The most interesting result is attained, when the power is deposited at the medium plasma radii. In that case the plasma heat conduction in the internal plasma part is so reduced, that it is hard to measure it. In order to reduce all tokamak results to one profile (Fig.5) it was necessary to normalize a current radius to the radius of the same field line twisting: $\rho=r/a$, where $a=\sqrt{\frac{IR}{Bt}}$, I is plasma current. Thus one can see that low m and n

MHD modes mainly cause the instability. Indeed, it torn out that no more than 10% of current passes outside the zone with q=m/n=2.

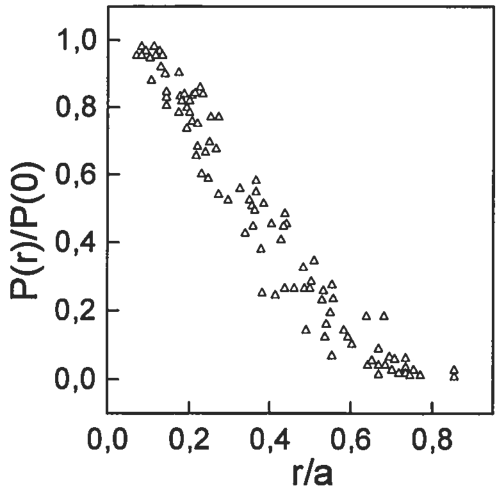

Fig.5. The dependence of relative plasma pressure, p(r)/p(o) on radius $\rho=r/a$*, where* $a=\sqrt{\frac{IR}{Bt}}$ *for different tokamak devices (T-10, T-11, TFR, TM-3, PLT, ASDEX,PDX).*

B.B.Kadomtsev has given a beautiful semi-quantitative description of the phenomenon, using variational principle, and proceeding from the fact that the large scale MHD-instabilities limited by non-linearity are a basis of the process [6]. This non-linearity gives birth to a noise, filling the plasma. Kadomtsev has written the equation, characterizing the plasma energy state and found the solution corresponding to the energy minimum by variational technique. One of the private solution well represents the observed relationships among plasma parameters. As one could expect, received by Kadomtsev plasma presser profile has somewhat lower gradient than experimental one, as boundary conditions were not taken into account.

In difference with other theoreticians B.B.Kadomtsev has considered a plasma state not under-critical one respective to the instability development, but the situation with the well developed non-linear instabilities. As a result of this the transport coefficients interrupt to be a function of local plasma parameters only, being dependent on what is going in the plasma as a whole.

If one would be a success to obtain reduced heat conduction, even in a narrow zone at plasma periphery, the boundary would be removed from the hot part of plasma, and plasma pressure profile close to an ideal one would be produced. Then we can expect a better confinement as a result. It appears to be possible. If we protect plasma from a flux of impurities from the wall and deposit high enough heating power in plasma, a spontaneous transition into a better confinement regime is realized. In that case narrow region of reduced transport coefficients appears at the periphery, and so steep gradients emerge at the same place. The profiles in internal part of plasma become more near to the ideal, and the confinement is improved.

4.INTERNAL THERMAL BARRIERS

In an ordinary situation (Ohmic heating for example), in plasma center $q(0) <1$. When the current density is monotonic $q(r)$ monotonously rises to the periphery. This provides the conditions for driving many instabilities. If we using non-inductive technique for the current drive, or with the help of skin-effect (current density profile during current increase) shell increase $q(0)$ the ordinary shape of saw tooth relaxation's will be distorted (Fig.3). First they become to be saturated, then, when q_{min} approaches unity, i.e. conditions are close to their stabilization, a noticeable improvement in confinement before each internal disruption is observed.

An opportunity to affect the current profile by current drive at electron cyclotron resonance (ECCD) in tokamak allows one to produce any profiles, including non -monotonous. In the central zone, in the last case, the shear value $S=\frac{r}{q}\frac{dq}{dr}<0$, that is beneficial from the view-point of stability. The zone with a negative S can be done rather large (up to $\rho=r/r_{plasma\ edge}=0.8$). As the tokamak experiments have shown, some small improvement in the confinement may be exist in the negative region, but, as a present from Nature, experimentalists received a new phenomenon: unexpected confinement increase due to producing "internal thermal barrier" in the vicinity to q_{min}. At many tokamaks such experiments have been done using an additional to Ohmic plasma heating technique by injecting of fast neutral atoms into the plasma with negative shear. Since the atomic beam has a longitudinal component, it introduces a rotation momentum into the plasma, and plasma starts to rotate with a high speed. The heat and particle confinement in such experiments has risen 2 –3 times (Fig.6 [7]) .

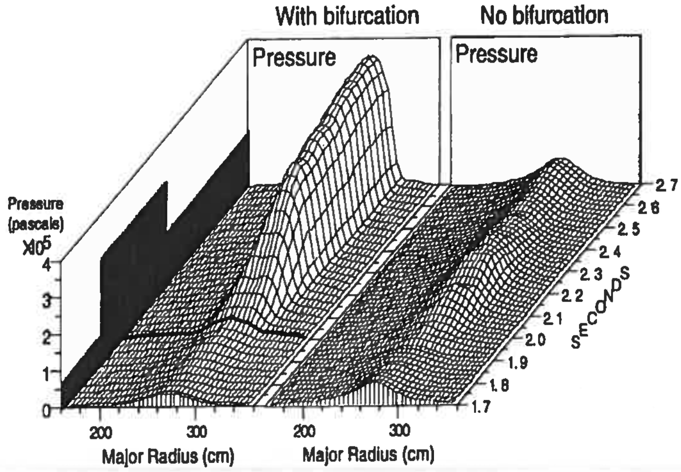

Fig.6. TFTR-tokamak. The plasma pressure profile changes during internal thermal barrier formation (left diagram), and usual regime (right one). Black contour shows time behavior of the deposited power.

The theory lays spatial emphasis on the inhomogeneous rotation rate (shear of rotation) in the process of the internal barrier formation. At T-10 tokamak (Kurchatov institute, Moscow [8]) the experiments were done with a successive rise in q_{min} under the ECCD current density profile control. In this case no momentum was introduced into the plasma in the process of q_{min} rise. When q_{min} , increasing, approaches to the rational values q=1; 1.5; 2…, a periodic (Fig.7)

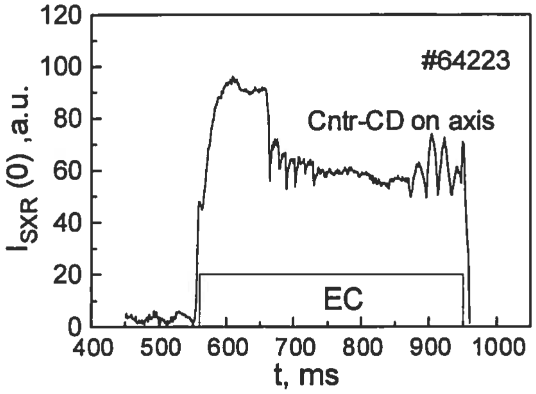

Fig.7. T-10 tokamak. Temporal behavior of $T_e(0)$ under off axis ECCD in opposite to main plasma current direction. The periodic confinement increase takes place at the discharge end when q_{min} approach 2. Internal disruptions with m=2 are seen at the discharge beginning.

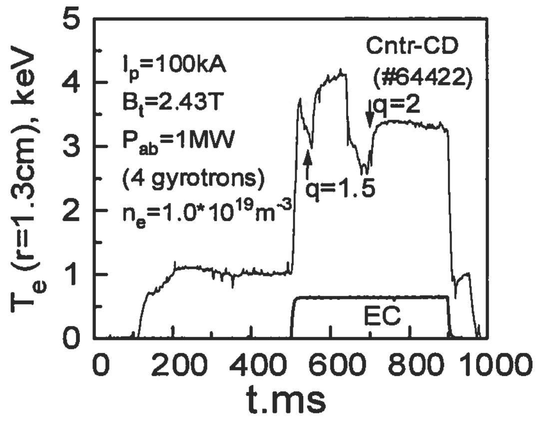

Fig.8. T-10 tokamak. Temporal behavior of $T_e(0)$ in the same case as in Fig.7, but for the conditions when q_{min} increase more rapidly from the discharge beginning to its end. One can see the transitions at q_{min} approaching 1.5 and then 2 values.

and then steady state (Fig.8) improvement of the confinement was observed in the central part of the plasma, within the surface q_{min}. The radiation intensity profile study in the soft X –ray range, I_{SXR}(r, E=3 –10 keV), has allowed one to follow the process of internal barrier formation with a good space resolution in these experiments (Fig.9).

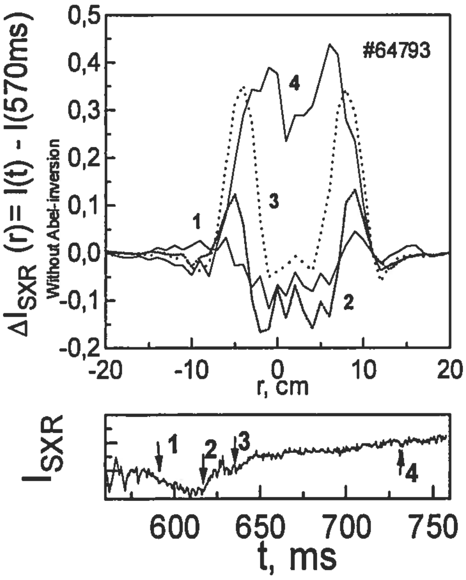

Fig.9. T-10 tokamak. SXR intensity profile changes in relation to t=570ms during the internal thermal barrier formation.

In order to make these processes to be more pronounced the X-ray intensity at the stationary stage, before the transition, has been subtracted from the subsequent intensities registered along the same chords. At the start-up of the transition the highest intensity increment ($I_{SXR} \propto T_e n_e^2$ in given measurements) has been observed in a narrow plasma ring within the surface q_{min}. Outside that surface, as well as at plasma center, the intensity first drops, even when the power of ECR-waves is deposited at the plasma center. The plasma temperature drop at the center remains to be unclear yet, since it corresponds to the heat flux against the temperature gradient.

An analysis of such experimental results has given one of very probable explanation: the barrier is produced due to increasing the distance between the magnetic islands and that of reducing the MHD activity in this zone. Such barriers can be organized between any rational surfaces with low values of m and n: q=m/n=1; 1.5; and so on. The highest effect of the confinement improving is attained in the vicinity to q=2. However, the improvement in confinement, as a result of such a process, is not great, about 30% only, in comparison with 200% achieved in experiments with a high rotation shear rate. Hence one can conclude that the anomalous high losses from the plasma are related not only with the specific features of its MHD structure but with some other instabilities more low scale ones.

A wide spectrum of the developed turbulent oscillations is observed in tokamak plasma. They can be excited by the MHD instabilities and by the kinetic sources related with deviation from the equilibrium in the particle distribution function. The turbulent plasma density oscillations are studied by scattering or by rejection from the critical density zone of high frequency electromagnetic waves. The spectrum of such fluctuations consists of a few types. The most characteristic of them is so-called “broad band” one characterized by a low coherence and represented practically at all studied frequencies, and a quasi- coherent mode, having the coherence level up to 60%. Of cause MHD modes related with islands can also be seen at the corresponding plasma radii in the range of low frequencies. All the oscillations, as a rule, rotate in the same direction, probably, together with the plasma.

The theory predicts the opportunity to stabilize such oscillations. When there is a strong gradient in the $\mathrm{E} \times \mathrm{B}$ flow, the turbulence, which normally have finite radial extent, are shorn apart, greatly reducing the transport. When the shearing rate, $\gamma_{\mathrm{E} \times \mathrm{B}}$, exceeds the decorrelation rate, predicted by linear theory, $\gamma_{lin}^{\max}$, the instabilities can be completely stabilized.

The behavior of a turbulent noise amplitude under the formation of an internal barrier, when it is no enhanced plasma rotation (experiments with ECCD at T-10 tokamak [9]), and when such a rotation is being produced (Injection of neutral atoms, TFTR-tokamak, Princeton, US, [8]) are shown in Fig.10. In the first case the noise is suppressed by a factor 20 – 30%. In the second case it is about 10 times, and, as we have seen, an essential increase in the confinement takes place.

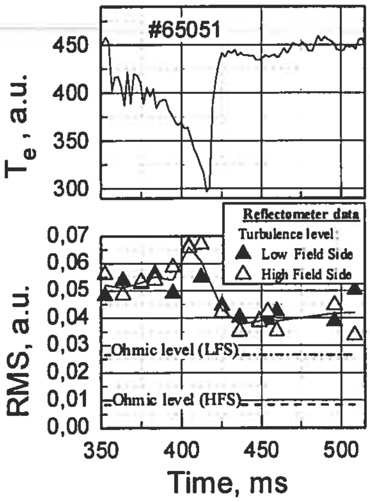

Fig.10 a. T-10 tokamak. The T_e and turbulent level temporal evolution during the internal barrier formation. The turbulence was measured both for low and high field side. Dashed lines show the turbulence level for the Ohmic heating stage.

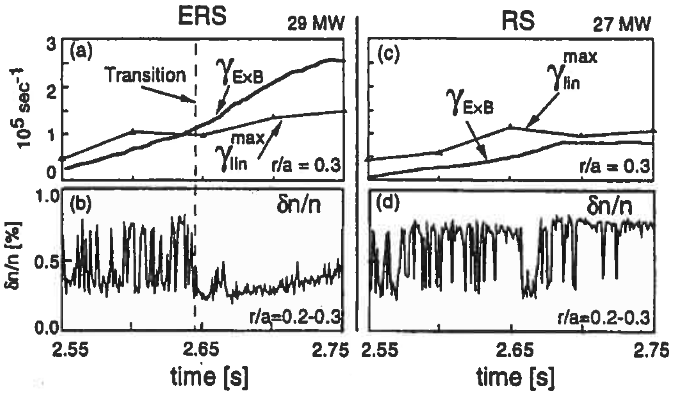

Fig.10 b. TFTR-tokamak. Suppression of the turbulent fluctuations after internal thermal barrier formation, when $\gamma_{E \times B} > \gamma_{lin}^{\max}$. The dashed line represents the time of transition (see Fig.6. also).

We can summarize. Controlling the $q(r)$ profile; one can produce, increasing a distance between the MHD islands, a zone of reduced MHD activity. This results in decrease of a part of anomalous heat flux across the magnetic field, and in the emergence of an enhanced plasma pressure gradient in such a zone. If the pressure gradient is rather steep, to be able to produce an enhanced rotation at the same part of plasma, and $\gamma_{E\times B}>\gamma_{lin}^{max}$, the turbulent flux will be also reduced, if not, the confinement will be improved due to the separation of the neighbor magnetic islands only.

5.CONCLUSION

The high temperature plasma with the current located in the strong magnetic field, (ρ_{Armor}<<particles free pass between collisions), produces, as a result of non-linear MHD instability development and the low scale turbulence related with it, a well-pronounced stationary structures of helical islands. The profiles of plasma parameters are determined by the self-consistent transport coefficient profiles. Some external forces are able to affect these profiles. In particular, one can produce some equilibrium configuration in which the transport coefficients will have local minima, i.e. to organize internal barriers.

The vary non-linearity in the development of plasma instabilities results in the fact that even the development of a turbulence in it does not result in the chaotic state of its behavior, does not destroy it, but, on the contrary, binds and stabilizes a self-consistent self-organized structures.

This allows one to produce on Earth plasma, within some limited volumes, with the temperature of up to 35keV (4×10^{8}°K), exceeding the temperature of Sun.

REFERENCES:

1.N.D.Vinogradova and K.A.Razumova, Plasma Phys. And Contr. Nuclear Fusion Res., v.II, p.617, IAEA, Vienna, 1966.

2. M.R. De Baar et al, Phys. Rev. Lett., 1997, 78, p. 4573.

3 B.B.Kadomtsev. Fizika plasmi, (Russian), 1, N5, p. 710, 1975

4 4. P.V.Savrukhin, E.S.Lyadina et al, Nuclear Fusion, v. 34, N3, p. 317, 1994

5 Yu.V.Esipchuk, K.A.Razumova, Plasma Phys. And Contr. Nuclear Fusion Res., v. 28, p. 1253, IAEA, Vienna, 1986.

6 B.B.Kadomtsev, in proceedings of International Conf. On Plasma Physic, IAEA, Vienna, p. 1273, 1987.

7. E.J.Sinakowski et al, Phys. Plasmas, 4, p. 1736, 1997

8. . K.A.Razumova et al, in proceedings of EPS Conf. on Plasma Phys. and Control. Nuclear Fusion Reserge Or 20, 1999.

9. K.A.Razumova, V.A.Vershkov and S.V.Soldatov, in proceedings of Satellite Meeting of 26th EPS Conf. On Control Fusion and Plasma Phys. 2nd Workshop «Role of Electric Fields in Plasma Confinement», p.2, Maastricht, 1999.