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Dissipative Nonlinear Structures in Tokamak Plasmas

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A lot of different kinds of instabilities may be developed in high temperature plasma located in a strong toroidal magnetic field (tokamak plasma). Nonlinear 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 means that the transport coefficients in plasma do not depend just on the local parameters, being a function of the whole plasma configuration and of the forces affecting it. By disrupting the bonds between separate magnetic surfaces filled with islands, one can produce zones of reduced transport in the plasma, i.e. "internal thermal barriers", allowing one essentially to increase the plasma temperature and density.

Keywords: Tokamak; Magnetohydrodynamic; Skin-effect; High temperature plasma

1. INTRODUCTION

High temperature plasma in a 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. In order to study such plasma, scientists are forced to produce it artificially. In particular, the plasma produced for creating a controlled fusion reactor is used. Among such plasmas, 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. Analogue configurations—but with lower particle temperature—may be seen in a Solar corona.

This paper is concerned with the information obtained on plasmas of such a 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 magnetohydrodynamic (MHD) instabilities are the most essential ones. Since a current in tokamak flows along the externally created toroidal magnetic field, the total magnetic field configuration has a helical structure, and its strength depends on the 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, and r is the current minor plasma radius. At some plasma radii, the field lines are closed to itself after m path tracings. They are also able 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 distortion of the corresponding magnetic field distribution. The islands can increase in size until nonlinear processes will not stop their growth. So the plasma acquires the rather hard, well-pronounced structure which can exist stationary.

The plasma, pierced with "snakes" with different m and n values, rotates in the poloidal and toroidal directions at the same time, with various velocities at different radii. Thus the MHD instabilities result in the production of the new stable configuration, which affects in its own way the plasma confinement. In Fig. 1 (De Baar *et al.*, 1997), the temporal evolution of such a picture is presented. The image of glowing plasma was reflected upon a fast-rotating film. One can see a large, probably $m = 3$, structure and a more fine structure at the plasma edge. The structures rotate in opposite directions. In this picture, it is impossible to see islands with $m = 1$ and $m = 2$, since the temperature in the plasma core is too high and plasma does not radiate in the visible range. They can be seen in the X-ray radiation range only.

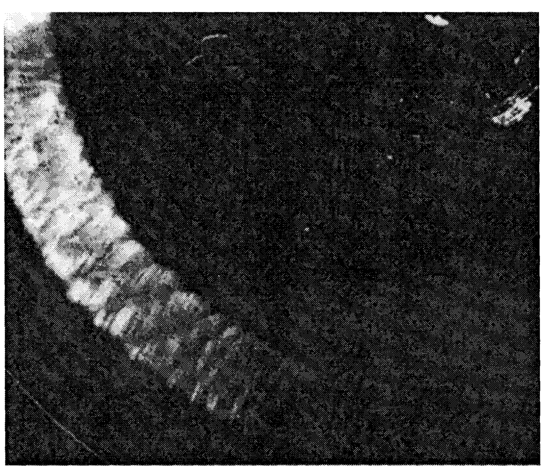

FIGURE 1 TM-3 tokamak. The temporal behavior of the image of the glowing plasma. The slit, looking at the plasma, was reflected upon the rotating film. The tine pusses from top left to bottom right.

The electron temperature profile measurements, made with a very good space resolution ($\Delta r = 0.3$ cm for $r_{max} = 20$ cm), have shown that the central part of the plasma, besides the resonance islands, is filled with thin threads of an inhomogeneous plasma: the so-called filaments (Esipchuk and Razumova, 1986).

The island size depends on the magnetic ????????? in the island region, dq/dr. The higher dq/dr is,??????? The adjacent islands can be linked at their ???????? complicated structures with high m and n, or can produce the zone with completely destroyed magnetic surfaces. This is essential for the rate of heat and particle transport across the magnetic field. In ideal, totally stable plasma under a 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 flows freely from insides an island to outside, 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 the 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 Kadomtsev (1975), let us divide the magnetic field into two components: one is in accordance with $q(r) = \text{const} = 1$, the other, B^*, is a poloidal field which provides a declination q from the unity: $q < 1$ inside S, and $q > 1$ outside it. Under infinite electro-conductivity, that configuration permits 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

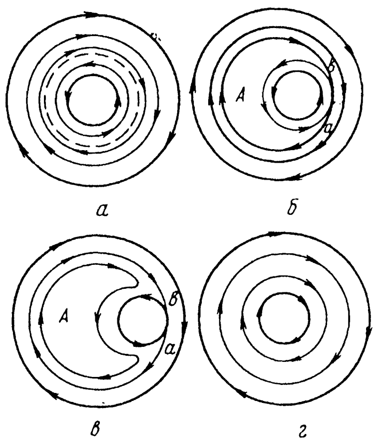

FIGURE 2 The behavior of the poloidal field B^* in plasma cross-section at different moments during internal disruption formation. At the beginning B^* has different direction inside and outside the surface $q = 1$. After the process of reconnection of magnetic field lines it has the same sign in the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

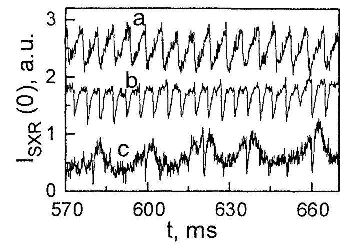

FIGURE 3 The temporal behavior of the central SXR intensity (a) for usual Ohmic heating regime, (b) and (c) for the regimes when $q_{\min}$ increase and approaches to unity (c).

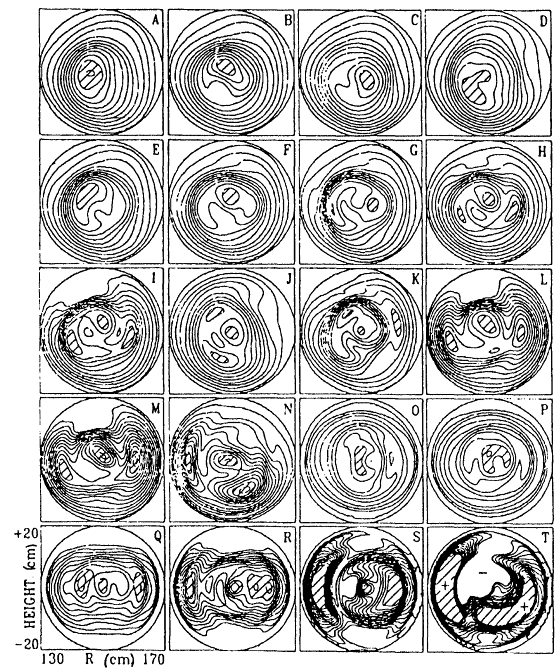

FIGURE 4 T-10 tokamak. The result of the tomografic reconstruction of the SXR profiles for three angles of registration. The successive instance during the disruption development begins at the top left and goes in alphabetical order. The time resolution is 10 mks. The time between pictures is 60 mks.

magnetic field lines reconnection will increase $q(0)$ up to 1 and push out of the surface S the central heat and poloidal magnetic flux (Fig. 2). 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 (Fig. 3a).

If the $q < 1$ zone is large, the process of the reconnection of magnetic lines may also include other islands with $m = 2$, or with higher m. Then the current and heat release from the plasma core can result in complete plasma disruption. In Fig. 4 (Kadomtsev, 1987), one can see the equal X-ray radiation intensity levels. This was obtained 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 the plasma structure with blow-out of the hot central part to the periphery of plasma at the end.

3. PROFILE CONSISTENCY

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

If the destabilizing factors are more or less standard for various tokamaks, we would be right to expect the emergence of the same type parameter profiles for various plasmas. This is illustrated in Fig. 5 (Razumova *et al.*, 1999a). 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 reduced to such an extent 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 $a = \sqrt{IR/Bt}$, I is plasma current. Thus one can see that low m and n MHD modes mainly cause the instability. Indeed, it tore out that no more than 10% of current passes outside the zone with $q = m/n = 2$.

B.B. Kadomtsev has given a beautiful semi-quantitative description of the phenomenon, using the variational principle and proceeding from the fact that the large scale MHD instabilities limited by

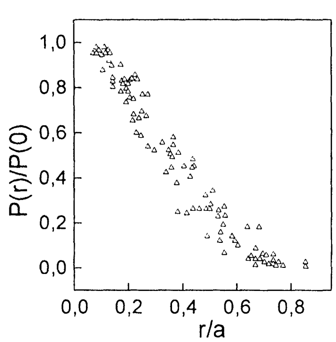

FIGURE 5 The dependence of relative plasma pressure, $\rho(r)/p(0)$ on radius $\rho = r/a$, where $a = \sqrt{IR/Bt}$ for different tokamak devices (T-10, T-11, TFR, TM-3, PLT, ASDEX, PDX).

nonlinearity are a basis of the process (Razumova *et al.*, 1999b). This nonlinearity 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 the variational technique. One of the private solutions represents well the observed relationships among plasma parameters. As one could expect, the plasma presser profile obtained by Kadomtsev has a somewhat lower gradient than the experimental one, as boundary conditions were not taken into account.

In contrast to other theoreticians, B.B. Kadomtsev has considered a plasma state not under-critical with respect to the instability development, but a situation with well-developed nonlinear instabilities. As a result of this the transport coefficients stop being a function of just local plasma parameters, instead being dependent on what is going in the plasma as a whole.

If reduced heat conduction could successfully be obtained, even in a narrow zone at plasma periphery, the boundary would be removed from the hot part of plasma, and a 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 a high enough heating power in plasma, a spontaneous transition into a better confinement regime is realized. In that case, a narrow region of reduced transport coefficients appears at the periphery, and so steep gradients emerge at the same place. The profiles in the internal part of plasma become closer to the ideal, and the confinement is improved.

4. INTERNAL THERMAL BARRIERS

In an ordinary situation (Ohmic heating, for example), in the 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 are using a non-inductive technique for the current drive, or with the help of skin-effect (current density profile during current increase) $q(0)$ shall increase and the ordinary shape of saw tooth relaxation will be distorted (Fig. 3). First it becomes 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 profile, including a non-monotonous one. In the central zone, in the last case, the shear value $S = (r/q)\times(dq/dr) < 0$, which is beneficial from the view-point of stability. The zone with a negative S can be made rather large (up to $\rho = r/r_{\text{plasma edge}} = 0.8$). As the tokamak experiments have shown, some small improvement in the confinement may exist in the negative region, but, as a present from Nature, experimentalists received a new phenomenon: unexpected confinement increase due to producing an "internal thermal barrier" in the vicinity to q_{min}. With many tokamaks, such experiments have been done using an addition to Ohmic plasma heating technique by injecting 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 at high speed. The heat and particle confinement in such experiments has risen two to three times (Fig. 6, Savrukhin *et al.*, 1994).

The theory lays spatial emphasis on the inhom ??????in the process of the internal barrier formation. At T-10 tokamak (Kurchatov Institute, Moscow (Sinakowski *et al.*, 1997) 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 the increasing q_{min} approaches the rational values $q = 1$; 1.5; 2..., a periodic (Fig. 7) 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, $I_{SXR}(r, \quad E = 3\text{–}10\,\text{keV})$, has allowed one to follow the process of internal barrier formation with a good space resolution in these experiments (Fig. 9).

In order to make these processes more pronounced, the X-ray intensity at the stationary stage, before 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 the 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 still

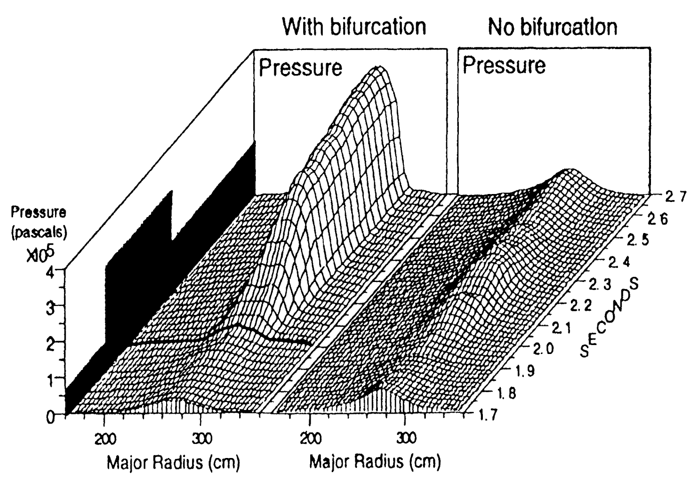

FIGURE 6 TFTR-tokamak. The plasma pressure profile changes during internal thermal barrier formation (left), and the usual regime (right). Black contour shows time behavior of the deposited power.

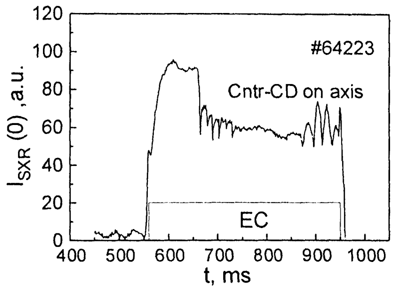

FIGURE 7 T-10 tokamak. Temporal behavior of $T_e(0)$ under off axis ECCD in the direction opposite to the main plasma current direction. The periodic confinement increase takes place at the discharge end when $q_{\min}$ approach 2. Internal disruptions with $m = 2$ are seen at the beginning of the discharge.

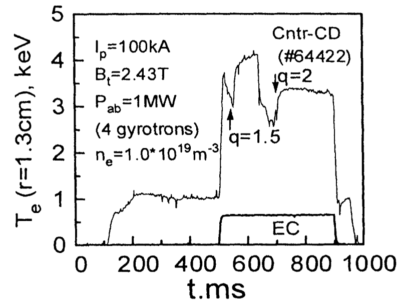

FIGURE 8 T-10 tokamak. Temporal behavior of $T_e(0)$ in the same situation as in Fig. 7, but for the conditions when $q_{\min}$ increase more rapidly from the beginning of the discharge to its end. One can see the transitions at $q_{\min}$ approaching values of 1.5 and then 2.

remains unclear, since it corresponds to the heat flux against the temperature gradient.

An analysis of such experimental results has given one very probable explanation: the barrier is produced due the increased distance between the magnetic islands and the reduction of 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 of $q = 2$. However, the improvement in confinement, as a result of such a process, is not great (only about 30%) 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 to the specific features of its MHD structure but to some other, lower scale, instabilities.

A wide spectrum of 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 the so-called "broadband" mode, characterized by a low coherence and represented practically at all studied frequencies, and a quasi-coherent mode, with a coherence level up to 60%. Of course MHD modes related to 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 E×B flow, the turbulence, which normally has a finite radial extent, is shorn apart, greatly reducing the transport. When the shearing rate, $\gamma_{E\times B}$, 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 there is no enhanced plasma rotation (experiments with ECCD at

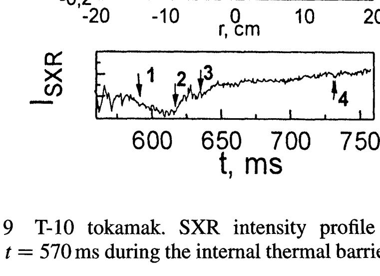

FIGURE 9 T-10 tokamak. SXR intensity profile changes in relation to $t = 570$ ms during the internal thermal barrier formation.

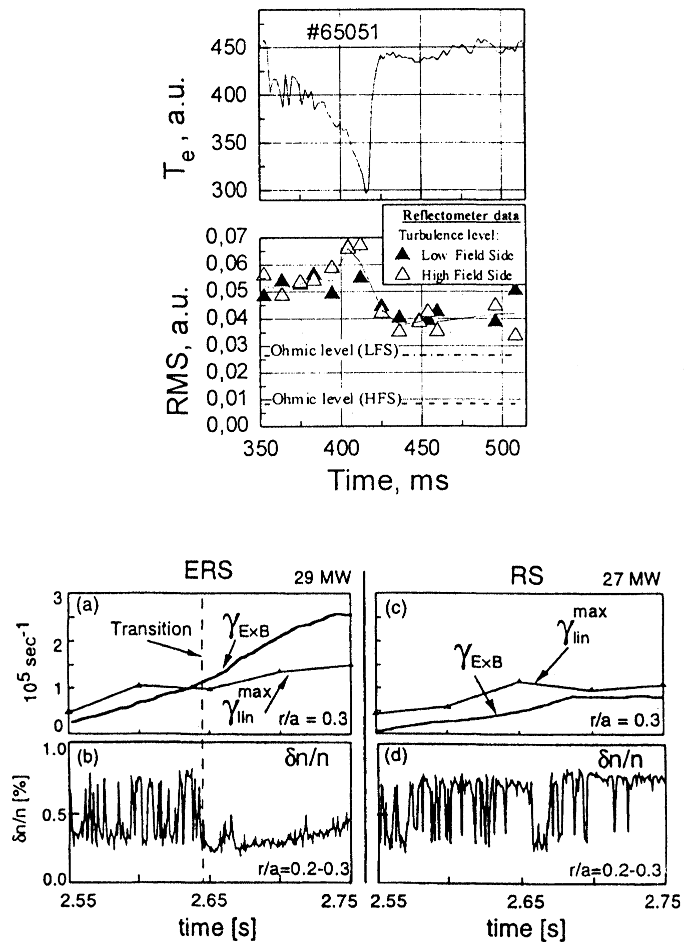

FIGURE 10 (a) T-10 tokamak. The T_e and turbulent level temporal evolution during the internal barrier formation. The turbulence was measured both for low and high field side. Dashed lines show the turbulence level for the Ohmic heating stage. (b) TFTR-tokamak. Suppression of the turbulent fluctuations after internal thermal barrier formation, when $\gamma_{E\times B} > \gamma_{lin}^{max}$. The dashed line represents the time of transition (see also Fig. 6).

T-10 tokamak (Vinogradova and Razumova, 1966), and when such a rotation is produced (Injection of neutral atoms, TFTR-tokamak, Princeton, US (Sinakowski *et al.*, 1997) is 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.

We can summarize as follows. Controlling the $q(r)$ profile; one can produce, increasing the distance between the MHD islands, a zone of reduced MHD activity. This results in a 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 $\gamma_{\mathrm{E\times B}} > \gamma_{lin}^{max}$, the turbulent flux will be also reduced. If not, the confinement will only be improved due to the separation of the neighbor magnetic islands.

5. CONCLUSION

The high temperature plasma with the current located in the strong magnetic field ($\rho_{\mathrm{Armor}} \ll$ particles free pass between collisions), produces, as a result of nonlinear MHD instability development and the low scale turbulence related to it, a well-pronounced stationary structure 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 nonlinearity in the development of plasma instabilities means that even the development of turbulence does not result in the chaotic state of its behavior or destroy it, but, on the contrary, binds and stabilizes a self-consistent self-organized structure.

This allows one to produce on Earth plasma, at limited volumes, with a temperature of up to 35 keV ($4 \times 10^{8\circ}$K)—exceeding the temperature of Sun.

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