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THE NATURE OF THE LARGE-SCALE INSTABILITIES IN THE TOKAMAK

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Experiments with excitation and investigation of macroscopic instabilities of a plasma column in Tokamaks are described. Instabilities arising on reduction of the stability margin $q(a) = H_z a/H_\varphi R$ down to a value of unity, and also instabilities arising when the critical concentration is exceeded and the equilibrium of the plasma loop is violated, are investigated by the correlation technique. The possibility of reducing all these instabilities to a single type, viz., to instability of resonance perturbations either at the boundary or near the boundary of the plasma column are considered.

1. INTRODUCTION

INTEREST in the investigation of large-scale plasma instabilities in Tokamak machines is due primarily to the fact that the main results obtained on containment[1, 2] and heating[3] of plasma in such systems pertain so far to a rather narrow working-regime region limited precisely by these instabilities.

If we base the classification of the instabilities on the external action causing the instabilities, then we can distinguish, first, the instability connected with the increase of the discharge current (at a fixed value of the stabilizing magnetic field); second, the instability arising when the plasma concentration increases above a certain critical value; third, the instability that develops when the equilibrium of the plasma column is violated, and finally the instability due to addition of impurities (Ar, Xe) or the deterioration of the vacuum conditions in the chamber.

Although all the foregoing instabilities are produced, as it were, by different causes, their consequences are approximately the same, namely the appearance of breaks on the oscillograms of the measured parameters, an increase of the plasma radiation, etc.

We point out in this paper certain facts that make it possible to suggest, in our opinion, a common nature of these effects.

2. FORMULATION OF PROBLEM

One of the probable causes of the development of macroscopic instabilities lies in the very nature of the helical structure of the magnetic field of the Tokamak, which is a superposition of the stabilizing toroidal field H_z (up to 40 kOe) and the field H_φ of the current-carrying plasma ring (0.5–2 kOe).

The parameter characterizing such a structure is ι — the twist angle of the magnetic force lines following a single circuit along the torus, or its reciprocal, the stability margin

$$q(r) = 2\pi/\iota = H_z r/H_\varphi R,$$

where r and R are the minor and major radii of the torus.

As shown by theoretical investigations carried out within the framework of magnetohydrodynamics,[4, 5] at such a configuration of the magnetic fields the plasma column can be stable only if q(a) on the boundary of the column exceeds unity (the Shafranov-Kruskal criterion). Even the first experiments confirmed qualitatively the need for satisfying this criterion.[6] When q(a) drops to unity, a sharp increase was observed in the fraction of the discharge current flowing to the limiting diaphragm mounted inside the discharge chamber, thus apparently evidencing powerful macroscopic instabilities of the plasma column. However, the condition $q(a) > 1$ turned out to be insufficient for the attainment of complete macroscopic stability of the column. A perfectly stable column was obtained only at $q(a) > 3$.[7]

Attempts were made, first of all, to explain such a difference by making use of a local criterion similar to the criterion for the stabilization of flute instabilities. It is known[8] that to stabilize the latter it suffices to satisfy the condition $q(r) > 1$ at all points of the plasma column. If we assume now a bell-shaped distribution of the current over the cross section of the column, then the quantity q(r) should decrease towards the center and it may happen that at q(a) close to three the value of q(0) drops to unity. Then it becomes possible for flute instabilities to develop at the center of the column, and these can lead to macroscopic perturbations. Thus, by generalizing the criterion $q(r) > 1$ to macroscopic instabilities, it is possible to obtain the minimum permissible value $q(a) \approx 3$.[7]

However, further development of the theory has made it possible to explain the existence of this limit also from another point of view. The point is that the quantity q(r) can assume integer values in the cross section of the column. This is physically equivalent to self-closure of the corresponding magnetic force lines after q circuits along the torus. Aggregates of such force lines form the so-called resonant magnetic surfaces (unlike the surfaces produced by unclosed lines).

It was shown in [9] that the formation of a resonant surface near the boundary of the plasma column can cause development of a macroscopic helical instability of the surface-wave type, much more dangerous than the flute instability. If we represent the helical perturbations of the plasma column in the form $\sim \exp i(\omega t - m\varphi + n\theta)$ (φ — azimuthal angle in the direction transverse to H_z, θ — in the longitudinal direction, and m and n are the corresponding azimuthal numbers), then the condition $q = m/n$ is satisfied for resonant perturbations whose pitch coincides with the pitch of the closed force lines. Since perturbations of the surface-wave type should develop near the resonant surfaces, this condition should be satisfied also for them. An important consequence of [9] is the conclusion that there exist at least three factors contributing to stabilization of these perturbations: first, the bell-shaped form of the distribution of the current over the cross section of the plasma column; second, the existence of a conducting sheath near its boundary; and third, the presence of a plasma with noticeable electric conductivity between the boundary of the column and the sheath.

The existence of stable resonant perturbations in Tokamak machines was observed by an optical method by Razumova and Vinogradova.[10] However, the question of how these perturbations are connected with the macroscopic stability of the plasma column remained open. To some degree, this question could be resolved by using a correlation method of investigating the spatial fluctuations of the magnetic field $\tilde{H}_\varphi$.[11] A system of magnetic probes was used to determine the shapes of the perturbations produced on the surface of the plasma column when the stability margin is decreased to $q(a) = 3$, and then also to $q(a) = 2$.[12] It was observed that when $q(a)$ is reduced to 3, resonant perturbations with $m = 3$ and $n = 1$ are produced on the surface of the plasma column. These propagate strictly across the magnetic field and have a "balloon" character, i.e., their amplitude increases on moving from the internal periphery of the torus to the external one. They have a tendency to grow and go over into an unstable regime. However, if the point $q(a) = 3$ is gone through rapidly, the column becomes stable again in the region $2 < q(a) < 3$, and only when the stability margin drops to $q(a) = 2$ do resonant perturbations with $m = 2$ and $n = 1$ appear and develop into a break instability.

These results agreed qualitatively with the notions developed in [9]. By analogy, it could be assumed that were it possible to overcome the resonance $q(a) = 2$, then an improvement of the macroscopic stability of the column would be obtained in the region $1 < q(a) < 2$. In addition, it was of interest to see which perturbations of the plasma column develop following instability with critical n_e and following loss of equilibrium.

3. EXPERIMENTS AT $2 > q(a) > 1$

The corresponding experiments were performed with the Tokamak-T-3A installation with $H_z = 20-30$ kOe, major radius of the discharge chamber $R = 100$ cm, minor radius 20 cm, and inside radius of the limiting diaphragm 17.5 cm. In the stable discharge regimes, the radius a of the plasma column was somewhat smaller than the radius of the diaphragm, and apparently ranged from 13 to 16 cm.

It was noted that in unstable regimes of the discharge with small values of H_z (~ 5 kOe) the discharge current was usually limited at a level corresponding to $q(a) \approx 2$ ($a \approx 17$ cm), and this was practically independent of the electric field on the axis of the torus. In some cases, however, at large electric fields, this limit was violated, and limitation of the current sets in already at double the level, corresponding to $q(a) \approx 1$. It can therefore be assumed that in the region $1 < q(a) < 2$ the plasma column had a larger stability than in the region of the resonance points $q(a) = 1$ and $q(a) = 2$.

An attempt was made to verify this assumption in the working region of the discharge regimes. It was proposed to overcome the limit $q(a) = 2$ by means of a pulsed increase of the discharge current, in analogy with the procedure used in [12], but from the level $q \approx 2$ rather than from the level $q \approx 3$. This was done by using a scheme developed by A. M. Anashin, which made it possible to increase the discharge current by $\Delta I = 100-150$ kA after 0.5–1 msec by successively switching capacitor banks.

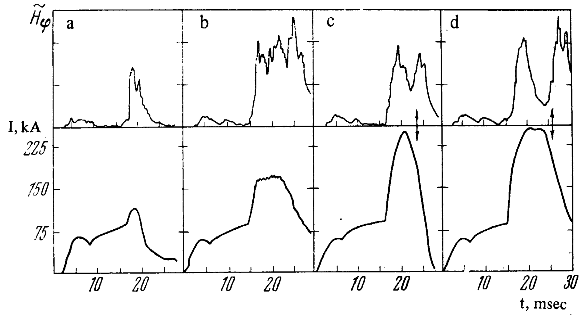

FIG. 1. Oscillograms of the signal proportional to the envelope of $\tilde{H}_\varphi$ for four variants of additional growth of the discharge current: a, b, c—successive increases of the current amplitude, d—increase of duration of ΔI. The arrows mark the instants of onset of the second durance.

Figure 1 shows oscillograms of the signals obtained with the aid of magnetic probes for different variants of the increase of the discharge current ΔI. The amplitudes of the signals are proportional to the intensity of the fluctuations of $\tilde{H}_\varphi$. The same figure shows the current oscillograms $I(t)$. The initial stage of the growth of the current to $q(a) \approx 2$ ($I \approx 100$ kA, $H_z = 25$ kOe, $a \approx 13$ cm)[12] remained unchanged in all cases. The current was increased in pulsed manner from this level by a specified increment ΔI.

As expected, the amplitude of the fluctuations of $\tilde{H}_\varphi$ first increased with increasing ΔI (Figs. 1a and b). This continued up to values $I \approx 220$ kA. With further increase of ΔI in the region of the largest I, a decrease of $\tilde{H}_\varphi$ was observed (Fig. 1d), and the $\tilde{H}_\varphi(t)$ curve assumed a characteristic form with two maxima. Such a behavior of $\tilde{H}_\varphi$ could be evidence, above all, of suppression of the instability with increasing I and with passage through the limit $q(a) = 2$, while the appearance of a second peak of $\tilde{H}_\varphi$ already on the decreasing part of ΔI indicates a second onset of this resonance. A similar picture is usually observed on going through the resonance $q(a) \approx 3$.[12]

A correlation analysis of the form of the perturbations,[11] carried out at the maxima of $\tilde{H}_\varphi$ (Fig. 2a), showed them to have a regular structure with $m = 2$, confirming by the same token the foregoing assumption. From this it follows directly that the instant of onset of the second resonance should depend on the duration of the pulse ΔI. This was observed experimentally (Fig. 1d).

A correlation analysis carried out at the minimum of $\tilde{H}_\varphi$ (Fig. 2b), reveals poorly-correlated, relatively small-scale perturbations. Since they have an apparent tendency towards damping, it is possible that at a sufficient duration of ΔI they become stabilized. But even without this assumption, it should be concluded that the macroscopic stability of the plasma column improves in the region $1 < q(a) < 2$.

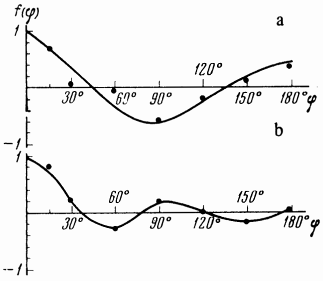

FIG. 2. Correlation coefficient $\overline{\tilde{H}_{\varphi 1} H_{\varphi 2}}/(\overline{H_{\varphi 1}^2}\,\overline{H_{\varphi 2}^2})^{1/2}$ against φ of the perturbations for the case shown in Fig. 1d: a–at the maximum of $\tilde{H}_\varphi$ with increasing current ΔI (m = 2), b–at the minimum of $\tilde{H}_\varphi$ on the plateau of the function $\Delta \dot{I}(t)$.

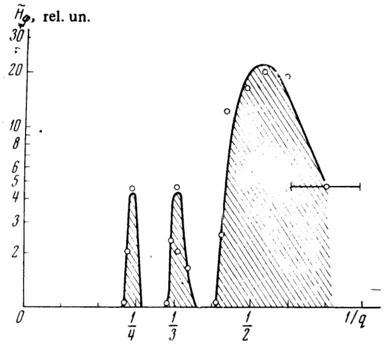

FIG. 3. Dependence of $\tilde{H}_\varphi$ on the parameter $\iota/q = l/2\pi$.

Attention is called to the fact that the effect of stabilization of the regular perturbations is observed at relatively large discharge currents (≈ 240 kA). Even if it is assumed that the radius of the column a increases with increasing ΔI up to the dimension of the limiting diaphragm (17.5 cm) then the value of I corresponding to the exact resonance $q = 2$ on the boundary of the column is approximately 200 kA. Thus, it is either necessary to assume that the column expands up to the walls of the discharge chamber (20 cm), or to conclude that in order for instability with $m = 2$ to develop it suffices that the resonance occur even at some distance (in our case 2–3 cm) from the boundary of the plasma column. The latter agrees with the mechanism of the development of instability of the surface-wave type.[9]

On the basis of the results, and also of the data of [12], we can plot $\tilde{H}_\varphi$ against $1/q = \iota/2\pi$. This plot is in fact a diagram of the discharge regions in the T-3A apparatus that are stable and unstable with respect to q. Such an attempt is shown in Fig. 3, where the unstable regions are shaded.

It must be emphasized that the value of $\tilde{H}_\varphi$, as shown in [12], depends not only on q but also on the method of exciting the instability, and therefore the intensity of the instability can be characterized by the quantity $\tilde{H}_\varphi$ only qualitatively. Nonetheless, the very existence of unstable regions at integer q points to the important, if not decisive, role of resonant perturbations in the problem of stability of a plasma column.

If we adopt this point of view, then a number of questions arise. First, why are the resonant perturbations inside the plasma column stabilized, and second, why do perturbations with $m > 3$, which are present during the initial stage of the discharge,[12] become stabilized during the quasistationary phase?

These questions can be answered by turning again to [9], where the factors leading to stabilization of macroscopic instability of the surface-wave type are listed. In particular, the stabilization of the instabilities with $m > 3$ in the quasistationary phase of the discharge can be related to the sharpening of the distribution of the current over the cross section of the column. Calculations show that if the distribution approaches parabolic $\sim [1 - (r/a)^2]$, then perturbations with $m > 3$ should be stabilized. A similar result was obtained for the dissipative helical instability of the "tearing mode" type. The dependence of the stabilization of the column on the current distribution was observed experimentally in [13].

On the other hand, there is one more mechanism, which can be significant for stabilization of perturbations with large m. It is known that the plasma column in the Tokamak rotates (along φ) with velocity 10^5–10^6 cm/sec.[10, 12] This velocity builds up during the initial stage of the discharge. As this velocity increases, the wall of the steel discharge chamber (liner) begins to play the role of the conducting sheath for the perturbations with large m, exerting a stabilizing influence on the latter. The influence of such a stabilization mechanism should increase with increasing thickness of the liner wall and with decreasing distance to the surface of the column. This may explain the results obtained with the American Tokamak ST,[14] where they succeeded in observing stable resonant perturbations with $m = 2$.

As to the stabilization of the internal resonant perturbations, it should be ensured apparently by the conducting-plasma layer lying between the corresponding resonant surface and the column boundary. Some indications in this direction are given by a study of the instabilities that develop with increasing plasma density above the critical value $n_{e.cr}$ and also of the instabilities that result from disturbance of the equilibrium.

4. INSTABILITIES RESULTING FROM INCREASING THE PLASMA DENSITY AND DISTURBING THE EQUILIBRIUM OF THE PLASMA COLUMN

The instability that arises when the plasma density is increased was observed already in [15]. It was revealed by breaks on the oscillograms of the column displacement, the derivative of the discharge current dI/dt, and the loop voltage.[16] Succeeding experiments have shown that the critical threshold $n_{e.cr}$ depends little on the discharge current and the intensity of the stabilizing magnetic field H_z (like $\sqrt{IH_z}$, for example, for T-3), but decreases noticeably when the vacuum conditions in the discharge chamber deteriorate or when heavy-atom impurities are added. Attempts to connect the excitation of this instability with the growth of β_I (the ratio of the gas-kinetic pressure of the plasma to the pressure of the magnetic field of the current H_φ) apparently turned out to be inconsistent, since no such instability was observed even in discharge regimes with β_I but with small concentration n_e.[17]

A correlation analysis of the fluctuations of $\tilde{H}_\varphi$ makes it possible to determine the structure of the perturbations preceding or accompanying any large-scale instability. It was used to clarify the character of the instability with critical value $n_{e.cr}$. First, in the stable discharge regime with $3 < q(a) < 4$, the plasma concentration was constantly increased from discharge to discharge up to $n_{e.cr}$. Whereas at small values of n_e the

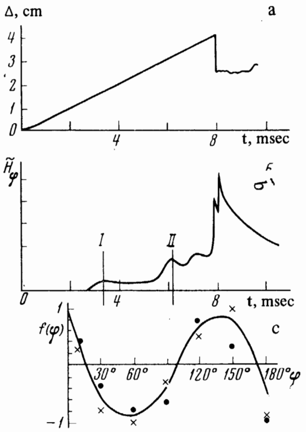

FIG. 4. Additional displacement of the column to the outside: a—oscillogram of column displacement Δ(t), b—dependence of $\tilde{H}_\varphi$ on t, c—coefficient of the correlation of the perturbations of $\tilde{H}_\varphi$ with respect to φ for two indicated instants of time (m = 3): X—instant I, ●—instant II. The time is reckoned from the instant when the transverse field is turned on.

instability was observed only during the initial stage of column formation (m = 4, 5, ...),[12] near $n_{e.cr}$ there were added to this instability intense perturbations that encompassed already the quasistationary phase of the discharge. With further increase of n_e, they led to a breakdown instability. The correlation analysis has shown that the additional perturbations had a helical structure with m = 3, distorted by the "balloon" effect. In experiments under worse vacuum conditions, the instability developed in similar fashion; the only difference was that $n_{e.cr}$ was lower.

In another series of experiments, cold hydrogen was injected pulsewise on the surface of the plasma column during the course of the discharge ($3 < q(a) < 4$). Some time after the start of the injection, the appearance of perturbations with m = 3, which subsequently developed into breakdown instability, was observed. A similar result was obtained when the equilibrium of the plasma column was disturbed by displacing it to the outside with a transverse magnetic field. Such a displacement should cause the edge of the column to touch the outer edge of the diaphragm.

As shown in Figs. 4a and b, after the column is displaced 1–2 cm an instability with m = 3 is excited (Fig. 4c), which likewise develops into breakdown instability. A decrease of the discharge current (increase of q) caused the instability to be observed only at a column displacement 4–5 cm. The developed perturbations had m = 4 and a strongly pronounced balloon character.

Thus, in experiments with injection, and also with displacement, where the periphery of the plasma column was subjected to external action, resonant perturbation modes developed, corresponding to those internal resonance surfaces which turned out to be closest to the column boundary.

Experiments with increase of n_e also fit in such a scheme, if it is assumed that at large concentrations the periphery of the plasma column can be strongly cooled by the radiation of the impurities. This is indicated by the results obtained in [18], where it was observed that not only the radiation power, but also the fraction of the radiative losses relative to the energy delivered to the plasma increases with increasing n_e. Apparently, the same occurs when the vacuum conditions become worse and when Ar or Xe is added to the hydrogen.

The resultant impression is that all the observed modifications of the macroscopic instabilities in Tokamak reduce to a single type—excitation of resonant perturbations either on the boundary or near the boundary of the plasma column. Their further development leads to a breakdown instability, the mechanism of which is not yet clear.

Of course, this conclusion cannot be final and, in principle, one can imagine that the development of the perturbation proceeds not from the periphery to the center but from the center to the periphery, with concomitant excitation of all the resonant modes. Further experiments should answer this question.

In conclusion, the authors consider it their duty to thank L. A. Artsimovich and V. D. Shafranov for valuable discussions, and are also grateful to A. M. Anashin for help during the performance of this work.

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