Elimination of MHD current instabilities of a toroidal plasma pinch by a feedback method

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(Submitted June 14, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. 26, No. 2, 89–92 (20 July 1977)

Experiments were performed on the elimination of the helical instability with the aid of a feedback system in an $l = 3$ stellarator (R-O) with ohmic heating. It is shown that introduction of a feedback system makes it possible to exceed the threshold of the development of the $m = 2$ instability and contain the plasma pinch in a new stable state.

PACS numbers: 52.55.Ez, 52.55.Gb, 52.35.Py

It has been shown experimentally that introduction of a feedback stabilization system makes it possible to increase the stability of a toroidal plasma pinch at

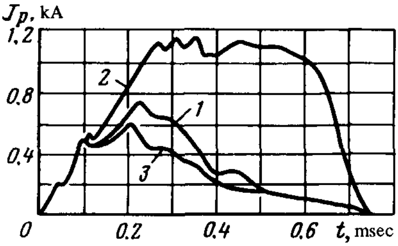

FIG. 1. Plots of $J_p(t)(i_0 \approx 0.8\pi$, $B_0 \approx 4.3$ kG); 1) feedback (FB) turned off; 2) feedback on, $\Delta\phi \approx 70°$, 3) FB on, $\Delta\phi \approx 230°$.

low values of the stability margin coefficient q, and to improve the plasma parameters.

One of the ways of optimizing the tokamak is to eliminate the MHD current instabilities so as to attain small $q \approx 1$. The possibility of dynamic stabilization of MHD current instabilities at small q, including the tearing instability, by means of rf magnetic fields has been demonstrated for the R-0 and RT-4 installations.[1,2] rf stabilization is broad-band, i.e., it ensures simultaneous stabilization of a large number of modes, but it calls for a relatively large expenditure of rf power. Dynamic control of the plasma stability by feedback does not require much power, but this method is narrow-band. The effective suppression of flute perturbations in the probkotron by means of an electrostatic feedback system was demonstrated by Chuyanov and co-workers.[3] No experimental demonstration of the effect of dynamic MHD control of the plasma stability in a toroidal trap, leading to optimization of the current discharge, has been performed to date.

The experiments on the elimination of the helical instability were performed on the R-0 $l=3$ stellarator with ohmic current heating.[1] The quartz chamber had $D=100$ cm and $d=10$ cm, the toroidal magnetic field was $B_0 \leq 8$ kG, the rotational-conversion angle was $i_0 \leq 1.6\pi$, the current in a plasma of duration $\tau \approx 0.8$ msec and magnitude $J_p \leq 1.5$ kA was excited with the aid of an air-core transformer. It is known that to eliminate the helical instability it is necessary that the feedback system have definite frequency characteristics and a definite gain.[4,5] For the experiments aimed at eliminating the helical instability we developed a six-channel feedback system comprising three pairs of helical windings with $m=1, 2, 3; n=1$, correcting amplifiers, and high-power output

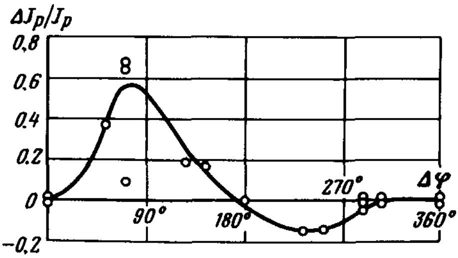

FIG. 2. Dependence of the relative change of the current amplitude in the plasma on the spatial phase shift.

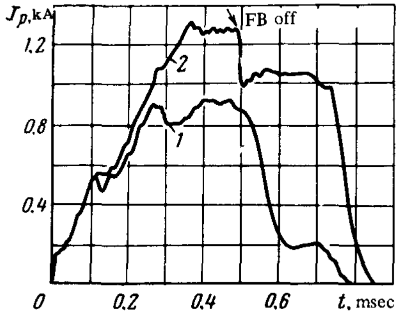

FIG. 3. Plot of $J_p(t)$ ($i_0 \approx 0.9\pi$, $B_0 \approx 4.7$ kG); 1) feedback off; 2) feedback on at the instant of time marked by the arrow.

current amplifiers. Each of helical windings consists of a "sine" and "cosine" winding shifted relative to each other by an angle $\pi/2$ along the major azimuth of the torus. Provision was made in the correcting amplifiers for summing the signals from the: "sine" and "cosine" windings with different weights. The output amplifiers delivered a current of 15 A to a 10-μH inductive load in the frequency range from 100 kHz to 1.5 MHz.

Prior to stabilization, the flow of current in the plasma was accompanied by development of helical stability. Experiments were performed to identify the modes of the helical instability. These experiments made it possible to determine those ranges of the stability margin coefficient $q_\Sigma(q_\Sigma = 2\pi/(i+i_j))$ at which are developed helical modes with $m=1,2,3; n=1.$[6] The obtained data agreed well on the whole with the conclusions of the theory.[7] It was observed, however, that the development of the fundamental unstable mode, e.g., $m=2$, is accompanied also by the development of oscillations with modes $m=1$ and 3 of small amplitude. It follows also from the experiments on the identifications that the perturbations of the magnetic field during the time of the instability development have nonzero phase velocities along the major and minor azimuths. This has made it possible to introduce a spatial phase shift and to vary the phase characteristics of the feedback system.

For effective action on the plasma we chose the mode $m=2$. When the feedback system was turned off, an increase of the current in the plasma to values corresponding to a stability margin coefficient $q_\Sigma = 2$ led to development of helical instability with fundamental $m=2$, the current stopped growing, and intense oscillations of the macroscopic parameters of the discharge were observed (Fig. 1, oscillogram 1). Turning on the feedback system made it possible to increase the stability of the discharge. This was accompanied by an appreciable increase of the amplitude and of the duration of the current (Fig. 1, oscillogram 2) and of the conductivity of the plasma. A stability-margin coefficient $q_\Sigma = 1.5$ was reached in the stabilized regime. Simultaneously with the 5- to 10-fold increase of the current, an increase took place in the amplitude of the helical oscillations with $m=1,2,3$. The presence of regular small-amplitude helical oscillations in the stabilized regime can be attributed to the limitation of the frequency characteristic of the regulators in the low-frequency region. This follows, in particular, from a preliminary analysis of the dispersion equation for the helical modes in an ideally conducting plasma in the presence of a feedback system.

We investigated the effect of a spatial phase shift $\Delta\phi$ on the stabilization. The dependence of the relative change $\Delta J_p/J_p$ of the current in the plasma on a gain $k \approx 1$ is shown in Fig. 2. The effect of destabilization in the case of a non-optimal phase shift is shown in Fig. 1 (oscillogram 3).

To ascertain whether the effect of the feedback system is limited only to an easing of the passage through the threshold of the instability development on the front of the current or whether it is necessary to maintain the plasma pinch in a new stable state, we disconnect rapidly the feedback after the current reached the maximum value (Fig. 3). It is seen that this leads to a decrease of the current in the plasma to the unstabilized value. At the same time, the amplitude of the helical oscillations with $m = 1, 2, 3$ increases sharply.

The experiments have thus shown that introduction of a feedback statilization system with appropriate phase characteristics makes it possible to increase the stability and to optimize the current discharge in a toroidal system. The corresponding currents in the control windings amount to $j_{contr} < 10^{-2} J_p$.

In conclusion, it is our duty to thank A. M. Abzianidze and the power-supply crew for ensuring uninterrupted performance of the experiments.

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