DYNAMIC STABILIZATION OF A PLASMA PINCH

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We describe experiments in which dynamic stabilization of a pinch carrying currents up to 10^5 A has been observed. The high-frequency stabilizing magnetic field is produced by the relatively slow damped discharge of a condenser bank through rods (located inside the discharge chamber) which surround the pinch. By means of a high-speed framing camera and magnetic probes it has been established that instabilities inherent to a current-carrying pinch are inhibited if certain specified conditions are satisfied.

IN the present work we report on results obtained in an experimental investigation of dynamic stabilization of a pinch.

It has been shown earlier [1] that this method can be used to achieve stabilization of longitudinal magnetohydrodynamic perturbations if the following conditions are satisfied by the stabilization system:

$$f > \frac{0.2I_0}{\lambda}\sqrt{\frac{\ln(\lambda/\pi r_0)}{2MN}} \qquad (1)$$

$$\frac{\partial \tilde{H}}{\partial r} > 0.2I_0\left(\frac{2\pi}{\lambda}\right)^2 \ln\frac{\lambda}{\pi r_0}, \qquad (2)$$

where f is the frequency of the stabilizing current in cps, I_0 is the current in the gas in amperes, λ is the wavelength of the perturbation in cm, r_0 is the radius of the pinch in cm, M is the ion mass, N is the number of ions over the cross section of the pinch per unit length, $\tilde{H}$ is the strength of the stabilizing ac field in oersteds.

These relations were obtained from an analysis of the equations describing the behavior of a "soft" pinch carrying current in a high-frequency field. The equations are analogous to those which describe the behavior of an inverted pendulum on an oscillating suspension; the stability conditions for the pendulum problem have been given in well-known work by Kapitza [2] and Jeffreys. [3]

However, the technological difficulties involved in producing intense high-frequency fields pose great obstacles for this method of stabilizing a high-temperature pinch. For instance, simple estimates made on the basis of (1) and (2) show that to stabilize a plasma current of several hundreds of kiloamperes it would be necessary to excite and support in the stabilizing winding a current with peak values of several tens of kiloamperes at a frequency of several megacycles per second. The rating of the generator required for such a system would be approximately 10^{10} VA.

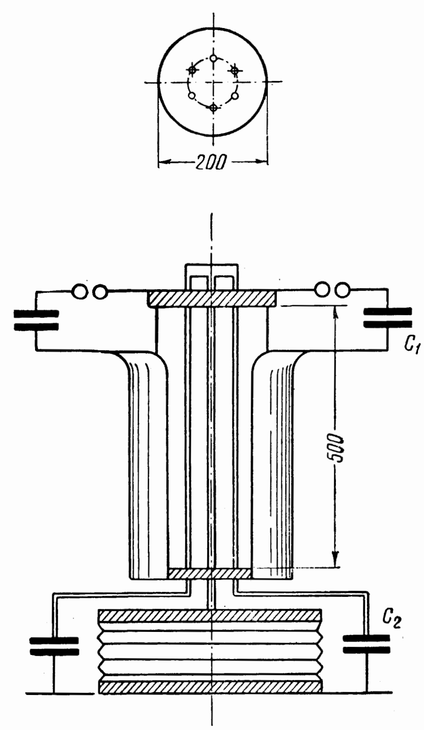

FIG. 1. Diagram of the apparatus.

The investigations described in the present work have been carried out with the purpose of studying some of the fundamental aspects of dynamic stabilization of a pinch in hydrogen at discharge currents up to 100 kA.

1. EXPERIMENTAL APPARATUS

The experimental apparatus consists of two circuits: the main discharge circuit and the stabilizing circuit (Fig. 1). The parameters of the main discharge circuit are as follows: D C_1 = 30-45 μF, U = 5-10 kV, T = 20-24 μsec. The discharge chamber is a glass cylinder with two

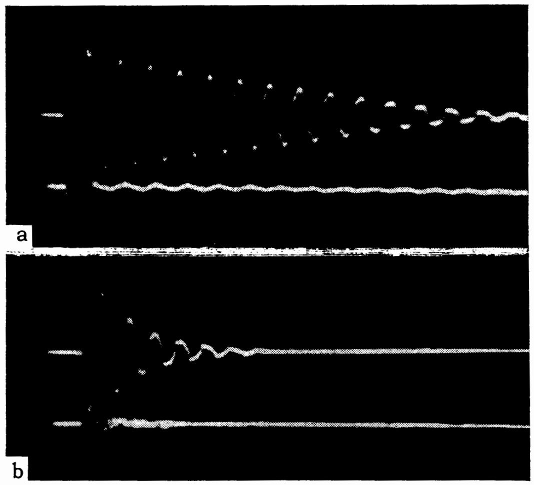

FIG. 2. Oscillograms of the oscillations in the stabilization circuit. The chamber pressures are as follows: a) $p_0 = 10^{-6}$ mm Hg; b) $p_0 = 0.1$ mm Hg.

electrodes which is filled with hydrogen to a pressure $p_0 = 0.05$-0.1 mm Hg. When the discharge is triggered a thin plasma pinch is produced at the axis of the chamber. The discharge chamber also contains six axial copper rods which are distributed uniformly at a diameter of 70 mm; these are insulated from the electrodes and from the plasma, and are excited through vacuum feed-throughs. The diameter of each rod (together with its insulation) is 10 mm. The rods in the stabilizing circuit represent an inductive load with an inductance of approximately 170 cm. The rods are connected so that the currents in adjacent rods are in opposite phase. The supply for the stabilizing circuit is comprised of modified KPM capacitors in which the quality factor has been increased ($Q \approx 60$-80); the total capacity $C_2 = 0.3$-$0.7\ \mu F$. When these capacitors are discharged through the stabilizing circuit by means of a vacuum trigger each of the rods carries a current of approximately 10-20 kA at a frequency of 0.5-0.7 Mc/sec; the capacitor voltage is 25-40 kV. The stabilization system, which is a damped oscillatory circuit, is triggered by means of an electronic delay system so that its trigger can be shifted with respect to the initiation of the main discharge by a specified time interval. It is well known [4] that in the initial stages a strong pulsed discharge is formed close to the walls of the chamber and that this discharge contracts towards the axis. The optimum phase for switching on the current in the stabilizing circuit is evidently the instant at

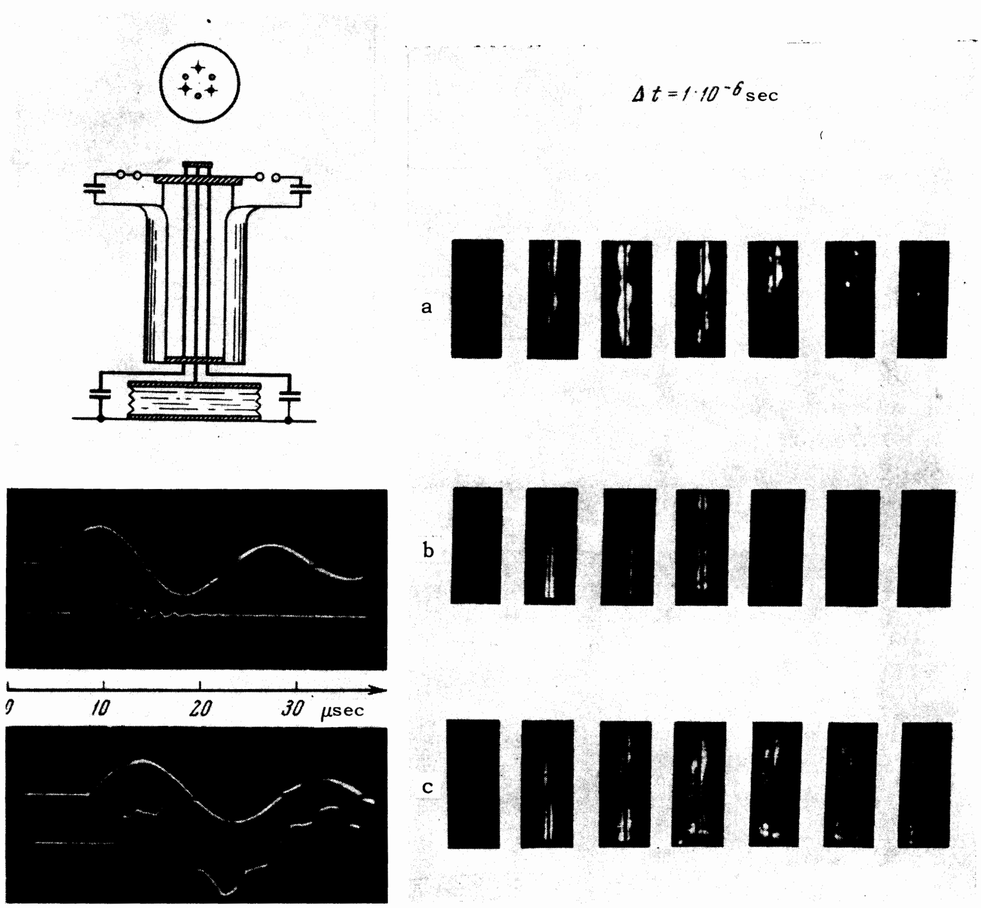

FIG. 3. Frames taken with high-speed camera. To the left, for clarity we have repeated the diagram of the apparatus and also give the oscillograms of the main current (upper trace) and the current in the stabilization circuit (lower trace).

a

b

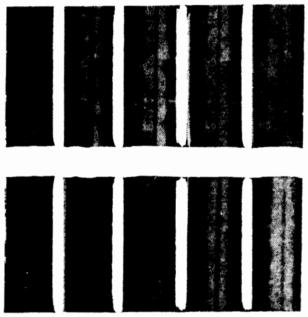

FIG. 4. Frames taken with a high-speed camera: a) without stabilization, b) with stabilization; $\Delta t = 10^{-6}$ sec.

which the contracting pinch passes through the region in which the rods are located.

The use of a discharge circuit driven by capacitors and the arrangement of the stabilizing rods inside the chamber (close to the pinch) represent an attempt to extend the range of dynamic stabilization to higher values of current.

It should be noted that the strong coupling to the load, which is the plasma in the present case, leads to a strong damping of the oscillations in the stabilizing circuit. In Fig. 2 we show oscillograms of the oscillations with a plasma (2b) and without a plasma (2a). In spite of these shortcomings experimental results concerning this effect were first obtained with a simple system of this kind. We may also point out that the dynamic-stabilization effect has been observed earlier by D. V. Orlinskiĭ.[5] A high-frequency vacuum-tube oscillator was used in his system. However, because of the relatively low power of the oscillator the effect could not be demonstrated effectively since the discharge current at which the stabilization appears is at least several kiloamperes.

2. EXPERIMENTAL RESULTS AND CONCLUSIONS

In Fig. 3 we show pictures taken with a framing camera through an aperature in the coaxial current conductor. The frames are taken at intervals of 10^{-6} sec. The first frame denotes an instant of time some 2×10^{-6} sec after initiation of the main discharge. In the absence of a stabilization current in the rods (Fig. 3a) one observes the characteristic pattern of pinch formation. The hydrodynamic instability inherent in such a pinch is clearly evident, being manifest in the kinking and curling of the pinch. With stabilization current in the rods (Fig. 3b) this deformation vanishes and the pinch maintains its shape without any visible distortion. To verify that the observed

a b

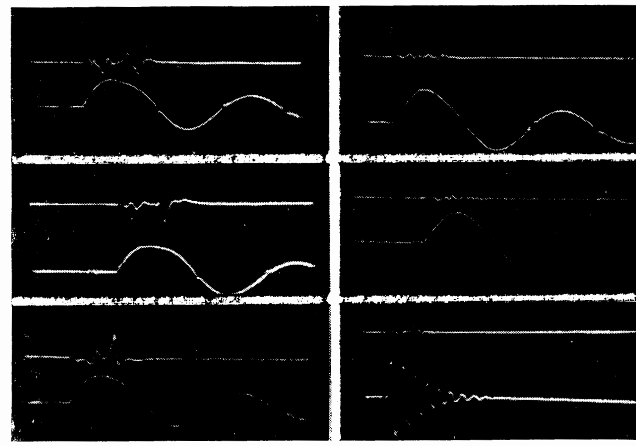

FIG. 5. Oscillograms of $\partial H_z/\partial t$ (upper trace) and curves of the discharge current (lower trace) 1a, 2a, 3a without stabilization, 1b, 2b, with stabilization, 3b shows the high-frequency noise in the upper trace produced in the absence of plasma.

effect really represents effective dynamic stabilization we have carried out control experiments in which relatively slowly varying currents flow through the rod (with peak values equal to that of the high-frequency current); these are switched on at the same phase with respect to the main discharge. In Fig. 3c we see framing photographs obtained in this case. The rods carry a current pulse formed by an artificial line. (The ringing on the oscillogram is caused by a mismatch with the load and is not important.) It is evident that the diameter of the pinch is appreciably greater in this case and that it is bent into separated plasma formations which are localized close to the rods.

All experiments shown in Fig. 3 were carried out with an initial hydrogen pressure $p_0 = 0.1$ mm Hg in the chamber. The peak discharge current is 50 kA and the first peak in the stabilizing current is 15 kA in each rod.

In Fig. 4 we show the development of the process in a stronger regime, in which the discharge current is 120 kA and the current in each rod is 22 kA.

In addition to observing the process photographically, we have carried out electromagnetic measurements which also verify the stabilization effect. For this purpose a coil 6 cm in diameter which surrounds the pinch is used to measure the pickup signal. It is known that kinking and curling of a pinch cause the appearance of a variable component of $\widetilde{H}_z$, the derivative of which then appears on the oscillogram. It is evident from Fig. 5 that in the presence of the stabilizing field

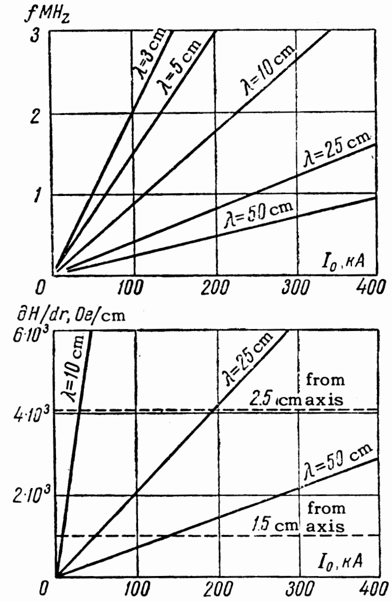

FIG. 6. Curve showing the relation between the stabilization criteria and the magnitude of the current being stabilized.

this signal does not exceed the noise level; without stabilization the signal becomes appreciable.

A comparison of the results of optical and electric measurements carried out with different values of the discharge parameters and the stabilization-circuit parameters yields completely satisfactory agreement between theory and experiment.

In Fig. 6, using actual experimental values for (1) and (2) we have plotted curves corresponding to the critical stabilization conditions as functions of the pinch current.

For currents of the order of 50 kA it is evident that the stabilization criteria are satisfied for practically all instability wavelengths. For currents of the order of 100 kA and higher the stabilization conditions are satisfied for a more restricted range of instability wavelengths. It is evident from Fig. 4b that in the presence of the high-frequency field the pinch does not exhibit any of the usual convoluted structure (up to times $\Delta t \sim 4\,\mu sec$) which appear in the same time interval in the absence of the stabilizing currents (Fig. 4a). Subsequently, however, as the amplitude of the stabilizing current decreases signs of deformation of the pinch start to appear.

Greatest interest attaches to extended confinement of the pinch at the chamber axis.

The strong coupling of the stabilization circuit to the plasma causes a strong damping of the oscillation, as has already been noted (cf. Fig. 2). In order to reduce the damping of the stabilization circuit we have used a low-inductance step-down transformer. The higher storage of energy in the primary circuit allows us to obtain an appreciable improvement (Fig. 7 and Fig. 2) with no reduction in frequency.

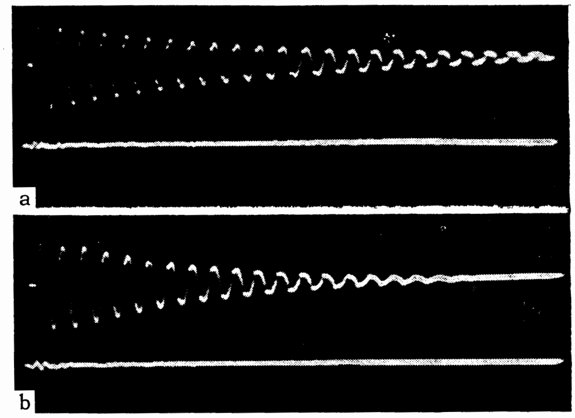

FIG. 7. Oscillograms of the oscillations in the stabilizing circuit using the low-inductance isolation transformer.

In Fig. 8 we show the effect of high-frequency magnetic field under the improved conditions; in this case, because of the decoupling transformer the oscillations continue for practically the entire first half-cycle of the main discharge.

It is evident from Fig. 8 that the pinch remains stable with respect to deformation perturbations of any wavelengths if the stability conditions are satisfied with respect to long perturbations. The photograph of the unstabilized pinch (Fig. 8a) shows that the instability starts with a kink deformation with the maximum possible wavelength and that the short-wave deformations appear

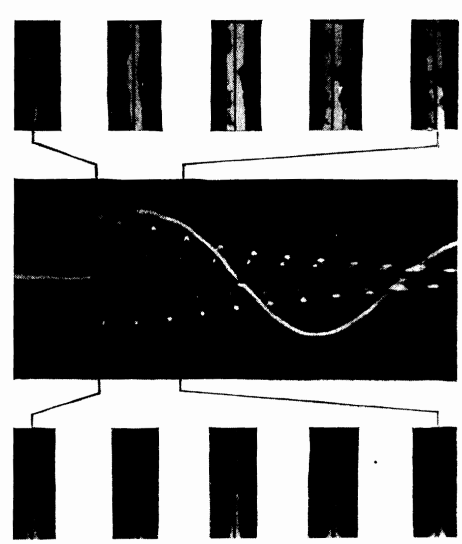

FIG. 8. Frame photographs in the system with the improved stabilization circuit.

later. This pattern of development of the instability is in contradiction with the linear theory, according to which instabilities of all wavelengths develop independently and in which the instability growth rate is larger at smaller wavelengths.

It follows from the theory of dynamic stabilization [cf. the inequalities in (1) and (2)] that this method is most effective for inhibiting longwave perturbations and that it is not well-suited for stabilization of shortwave instabilities. Thus, dynamic stabilization may not provide stability at all wavelengths; however, it can be used in conjunction with other methods, for example stabilization by a longitudinal stationary magnetic field which, as is well known, is best suited for the stabilization of shortwave perturbations.

The experimental results reported here indicate the need for further checking of our ideas and for formulating a theory which will be in better agreement with experiment. At the present time the approach to this problem is not completely clear. Nonetheless, in our opinion the results reported here provide some justification for assuming that this method of stabilization is effective with respect to magnetohydrodynamic instabilities of all wavelengths.

One might ask whether the additional fields used in this method do not cause complications in the form of new instability problems. The answer to this question can only be given after additional theoretical and experimental work has been carried out.

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