SUPPRESSION OF INSTABILITIES IN A PINCH

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It is shown experimentally that under certain conditions the use of a rapidly varying magnetic field can stabilize a straight pinch carrying a current of 100–120 kA. The stabilizing circuit consists of six bus bars located symmetrically on the outer surface of the discharge chamber, which is 20 cm in diameter. The conclusion concerning stabilization is drawn on the basis of data obtained by means of streak photographs of the emission, by magnetic probes, and by a transducer which records the energy lost to the chamber walls.

It has been shown in experiments described earlier[1] that a magnetohydrodynamic instability characteristic of a current-carrying pinch can be stabilized by means of an external rapidly varying magnetic field; the technique is known as dynamic stabilization. In the experiments reported in [1] the dynamic stabilization was realized in a system which had an important shortcoming; specifically, the stabilizing rods were inside the discharge chamber and could perturb the structure of the pinch in its formative stage. It appeared desirable to obtain the stabilization effect in a discharge with the same basic parameters (peak current approximately 100 kA, chamber diameter 20 cm and chamber length 60 cm) but under more hygienic conditions, with the stabilization rods outside the discharge chamber. In the present work we report on the results of an investigation of a system of this kind.

1. EXPERIMENTAL ARRANGEMENT

As compared with the version described earlier,[1] the use of stabilizing rods outside the discharge chamber means a reduction in the coupling between the stabilizing circuit and the pinch. In order to satisfy the dynamic stabilization criterion given in [2] it is then necessary to increase the power supplied to the stabilizing circuit. The criterion for dynamic stabilization can be written as follows:

$$f > \frac{0.2I}{\lambda}\left(\frac{\ln(\lambda/\pi r_0)}{2MN}\right)^{1/2}, \tag{1}$$

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

where f is the frequency of the stabilizing circuit in Hertz, I is the current in the gas in amperes, λ is the wavelength of the perturbation in centimeters, r_0 is the radius of the pinch in centimeters, M is the ion mass, N is the number of ions in the cross section of the pinch per unit length and $\tilde{H}$ is the stabilizing field in oersteds.

The condition in (1) is satisfied to the same extent as in the system described in [1] since the basic stabilizing current I is maintained at the same level while the frequency is made somewhat higher. As far as the condition in (2) is concerned, we note that to satisfy this condition it is required to approximately double the current in the stabilizing conductors. For this purpose, we make use of a Marx system, which allows us to double the operating voltage on the stabilizing rod with the same capacitance, 0.6 μF. The rods of circular cross section have been replaced by wide bus bars; with regard to the external location of the stabilizing rods this means that the inductance of the total system can be reduced so that rapidly varying magnetic field can be used more effectively. For a conductor of circular cross section the field in the immediate vicinity of the conductor falls off as $H(r) \approx 1/r$ whereas in a wide bus bar (or width a) the rate of decay is much slower: $H(r) \approx \arctan \times (a/2r)$. Under actual conditions, in the first case the maximum magnetic field near the conductor is essentially useless since there is always some gap, determined by the thickness of the insulation, the thickness of the walls of the discharge chamber, and so on. In the second version, which provides a smooth variation of the magnetic field close to each of the bus bars, with a favorable ratio Δ/a (a is the width of the bus bar and Δ is the gap between two neighboring bus bars) it is possible to o obtain a magnetic system in which the absolute magnetic field $|H_\perp| = \sqrt{H_\varphi^2 + H_r^2}$ is independent of the angle φ.[3] In the system described here six bus bars are used and the ratio $\Delta/a = 0.5$.

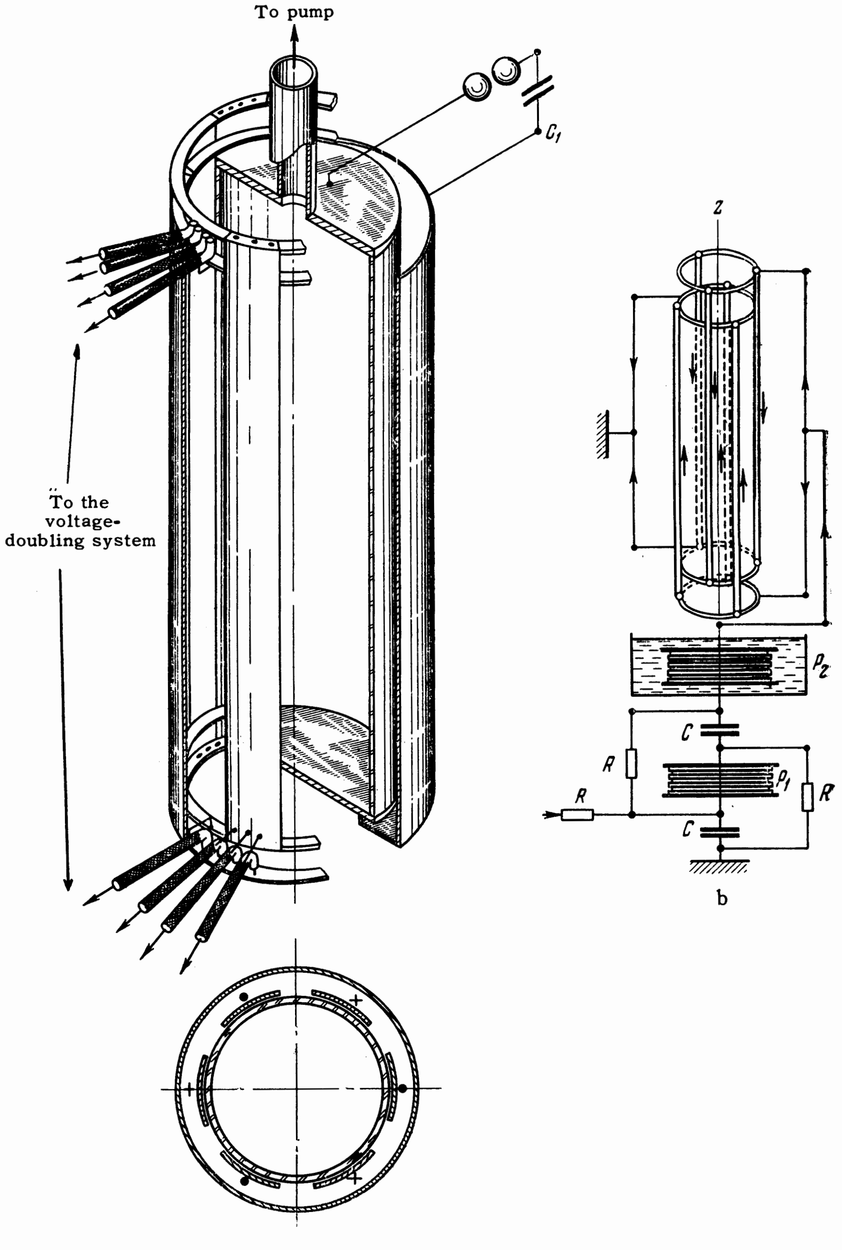

FIG. 1. Schematic diagram of the discharge chamber (a) and supply system for the stabilizing circuit (b).

Figure 1 shows a cross section of the experimental device and an electrical schematic diagram for the main circuit and the stabilizing circuit. The discharge chamber is a glass cylinder 20 cm in diameter and 60 cm long which is closed at both ends by plane electrodes. The gas is admitted and exhausted through one of the electrodes. The stabilizing circuit consists of six bus bars arranged around the profile of the external surface of the chamber. A system of 36 RK-6 cables is used to connect the stabilizing system to a bank of high-Q capacitors with a total capacity of 0.6 μF (at the voltage doubling time). The connections are such that the current in alternate bus bars flows in opposite directions. At a frequency of 700 kHz the maximum current in each bus bar is approximately 27 kA. The quality factor of the stabilizing current with the discharge switches is $Q \approx 20$. The voltage doubling arrangement (Fig. 1b) is made up of two vacuum discharge switches P_1 and P_2 one of which (P_2) is immersed in an oil tank in order to avoid breakdown at the surface when the voltage is doubled. Provision is made for triggering the basic discharge by means of an electronic delay unit which also triggers the stabilizing system; thus, it is possible to control the time at which the high-frequency current is applied with respect to the time at which the main discharge is fired. We recall the parameters of the basic discharge circuit: $C_1 = 70\ \mu$F, $U = 8-12$ kV and $T = 38\ \mu$sec.

2. METHOD OF INVESTIGATION

Three methods have been used to carry out the investigation reported here: streak photography of the emission from the discharge, detection of the field H_z, which is produced as a consequence of necking and kinking of the pinch, and measurement of the energy flux incident on the chamber wall due to the flow of current.

The photographic method gives an idea of the diameter of the pinch in terms of the emission and makes it possible to monitor the time interval that the pinch remains localized at the chamber axis. The slit in the camera system is oriented perpendicularly to the axis of the discharge. A transparent longitudinal break is provided in one of the bus bars. The observations are made through this slit and the neighboring gaps between the bus bars.

The signals produced by the H_z field are picked up by a coil which is wound around the chamber. After integration the signal is applied to the plates of an oscilloscope and from it is derived a quantity proportional to the φ-component of the pinch current.

In order to measure the time at which the pinch starts to interact with the walls and in order to determine the rate of energy loss from the pinch, use has been made of a so-called thermal probe which has been described earlier by Prokhorov.[4] The basic element of the thermal probe is a diaphragm which is heated to $T \approx 1500°C$. The diaphragm is a thin platinum foil six μ thick with a working area of 1 cm^2. The thermal probe is mounted in the side wall of the chamber approximately midway up the side wall. The plane of the diaphragm coincides with the inner surface of the chamber. The energy flux incident on the diaphragm increases its temperature and emission brightness. This light pulse is applied, through a light pipe, to the cathode of a photomultiplier located beyond the diaphragm. The signal from the photomultiplier is amplified and applied to the plates of an oscilloscope which then reproduces a curve characteristic of the energy that reaches the chamber walls. By preliminary heating of the diaphragm, which is necessary in order to enhance the sensitivity, it is possible to make the spectral distribution of the emission from the diaphragm correspond approximately to the region of greatest sensitivity of the photomultiplier cathode. The response time of the diaphragm must be much greater than the characteristic detection time for the process and is several microseconds under the conditions described here. The resolving time, which is defined as the time required for the pulsed heating of the diaphragm, is less than 0.5 μsec.

The thermal probe can also be used for quantative measurements. For preliminary calibration the diaphragm is pulse-heated by current pulses of known magnitude. This method makes it possible to record energy fluxes down to 0.005 Joules/cm^2.

It should be noted that in operation of the device with the stabilizing system, by using the oscilloscope it is possible to control the phase at which the stabilizing system is switched on. This system makes it possible to provide synchronization for all of the monitoring processes described here.

3. RESULTS OF THE MEASUREMENTS AND DISCUSSION

It is evident from the streak photographs of the emission (Fig. 2) that the joint operation of the basic circuit and the stabilizing circuit causes the pinch to remain close to the axis for about 6 μsec; when no stabilization is used this time is reduced by approximately a factor of two.

In Fig. 3 the sweep for the emission is synchronized with the discharge current and with the signal produced by the H_z field which arises when

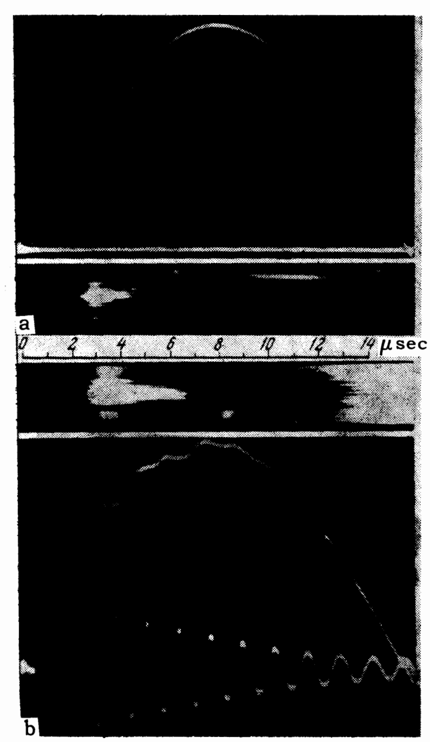

FIG. 2. Streak photograph of the emission from a pinch carrying a current of 120 kA for an initial hydrogen pressure of 0.1 mm Hg (a, without stabilization; b with stabilization). The time scale refers to the streak photographs and to the oscillograms of the current in the primary and stabilizing circuits.

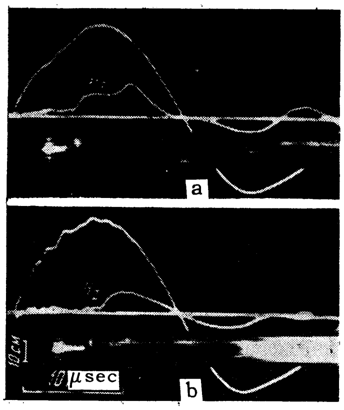

FIG. 3. Streak photograph of the emission from the pinch synchronized with an oscillogram of the current of the primary discharge and the instability signal (H_z): (a) without stabilization, (b) with stabilization.

the pinch becomes deformed. It is evident, that both in the free regime, in which the stabilizing circuit is switched off (Fig. 3a), and in the regime in which both circuits are operated (Fig. 3b), the sharp rise in the H_Z field corresponds to the time at which the pinch is broken up. The emission, which is localized in the region of the axis, disappears under this condition. It should be noted that in the free regime the pinch is broken up soon after it is formed; more precisely, at the time at which the current curve exhibits the double break characteristic of these discharges. When the high frequency magnetic field is applied the time at which breakup starts is displaced almost to the peak current. In Fig. 4, we show oscillograms of the current as well as the curves which describe the loss of energy to the wall. (The dashed curves are obtained by differentiation of the probe signals and give an idea of the rate at which energy is lost from the pinch.)

These oscillograms show clearly the lag in the energy loss to the wall when the stabilizing system is on. If we assume that each unit surface of the inside of the chamber receives approximately the same amount of energy, then by using the absolute calibration of the transducer we can estimate the energy loss to the walls when the pinch breaks up. In the first half cycle of the basic current this figure is approximately 0.25 of the total energy fed to the capacitor bank in the primary circuit and corresponds to the quantity calculated from the well-known relation $I^2 = 4c^2NT$.

A comparison of the results obtained by the different methods indicates that stabilization can be achieved under certain definite conditions in a discharge with a hydrogen pressure of 0.05–0.1 mm Hg and currents up to 100 kA if the high-frequency current is switched on at the appropriate phase. This stabilization is manifest in the fact that a pinch 3–3.5 cm in diameter is maintained at the axis of the chamber practically up to the time at which the discharge current reaches its peak value. Judging from the signals due to the H_Z field, the pinch does not kink or neck during this time period; the thermal transducer records the appearance of energy at the chamber walls only after the peak discharge current is reached. It is in this sense that one can say that the pinch is stabilized. It should be noted that stabilization is not observed if the high-frequency circuit is switched on later, that is, say, at some time after the peak compression of the pinch is reached when

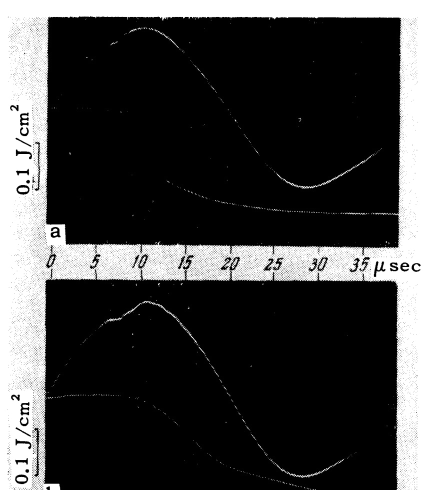

FIG. 4. Signals from the thermal probe (lower curves) taken together with the current in the primary discharge 120 kA (upper curves): (a) without stabilization, (b) with stabilization. The dashed lines show the energy loss to the walls.

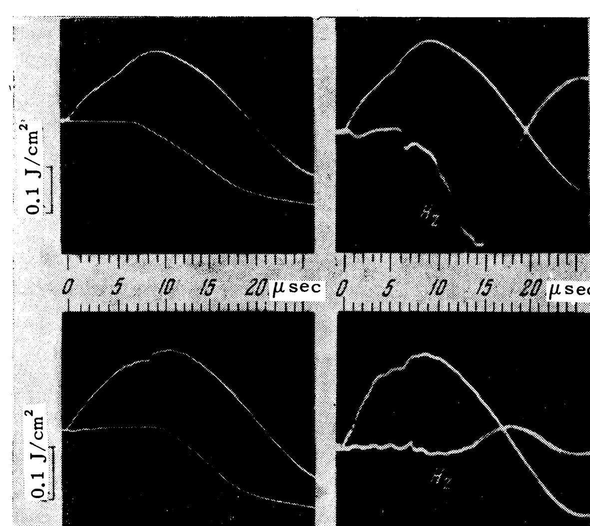

FIG. 5. Oscillograms of the discharge current up to 100 kA (upper curves): (a) signal from a thermal probe, (b) signal from the H_z field (lower curves). The hydrogen pressure is 0.05 mm Hg; upper curves, without stabilization, lower curves, with stabilization.

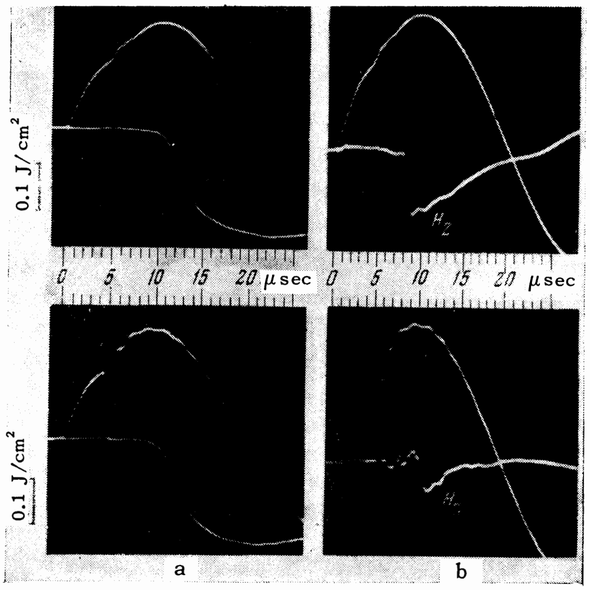

FIG. 6. Oscillograms of the discharge current up to 150 kA (upper curves): (a) signal from a thermal probe, (b) signal from the H_z field (lower curves). The hydrogen pressure is 0.05 mm Hg; upper curves, without stabilization, lower curves, with stabilization.

the pinch itself has already started to become deformed. If the stabilizing system is switched on too soon the effect is lost again because the magnitude of the high-frequency field is not sufficient for stabilization at the time the pinch is formed at the axis (due to the low quality factor of the high-frequency circuit).

If the phase corresponding to maximum compression of the plasma column is approximately the same as that for maximum current, as is the case when dI/dt is small in the primary discharge, the stabilization effect is not observed; after the peak in the basic current (descending part of the curve), the pinch is evidently not subject to the stretching effect of the self-magnetic field. From this point of view it is interesting to note certain experiments in which compression occurs long before the basic current has reached its peak. However, with all other conditions being equal the peak basic current is increased in this case and this can lead to a violation of the dynamic-stabilization criteria.[2] Under the conditions described here this violation evidently occurs at discharge currents of 150 kA.

In Figs. 5 and 6 we show, for purposes of comparison, oscillograms of the signals from the thermal probe and the H_z field for currents of 100 and 150 kA. Whereas in the first case it is possible to see a difference in the nature of the corresponding oscillograms taken with and without stabilization, it is evident that at 150 kA the curves obtained with the thermal probe (Fig. 6a, upper and lower curves) are essentially the same. We note in contrast with the more complete stabilization (Fig. 5b, lower curve) that a small signal due to the H_z field appears when the stabilizing circuit is switched on (Fig. 6b, lower curve).

One of the basic shortcomings of the system described here is the fact that the stabilizing current appears in the growth regime, at which time the amplitude of the stabilizing magnetic field falls off relatively rapidly. Without using a high-power generator with a long damping time it is difficult to judge the usefulness of the method of stabilization described here, as far as high plasma currents are concerned. On the other hand, this circumstance complicates a quantitative comparison of the experimental results with theory. It should also be noted that when the stabilizing power is increased the side effects associated with the high-frequency discharge become more important. It is possible that in further work this circumstance will require the introduction of appropriate corrections into the theory of dynamic stabilization itself.

In conclusion we wish to thank S. M. Osovets for his continued interest in this work and for discussion of the results.

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