TOROIDAL DISCHARGE IN A STRONG MAGNETIC FIELD

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The results of an investigation of a plasma loop formed in a toroidal chamber with a strong magnetic field are given. When the Shafranov-Kruskal stability condition is satisfied no macroscopic oscillations are observed. The radiation emitted by the plasma in the visible and ultraviolet regions of the spectrum has been studies. It is shown that in a metal chamber with a limiting vacuum of 1 to 2×10^{-6} mm Hg most of the radiated energy is due to impurity ions.

1. INTRODUCTION

A current pinch in a plasma is known to be unstable. A magnetic field is required for stabilization of such a system. One approach is to use a longitudinal field which is uniform over the cross section of the chamber.[1] In this case, H_0, the magnetic field over the entire cross section of the chamber, must be greater than the field due to the discharge current $H_J = 2J/ca$, where a is the radius of the pinch. As has been shown by Shafranov,[2] for stable operation the following condition must be satisfied:

$$H_0 / H_J \geqslant L / 2\pi a, \tag{1}$$

where L is the length of the pinch. In the case of a plasma loop formed in a toroidal chamber of radius R, we have $L = 2\pi R$. If the condition in Eq. (1) is satisfied in the toroid, instabilities characterized by wavelengths $\lambda \sim 2\pi R$ and shorter are suppressed. This method of stabilization, however, does not provide absolute stability. Certain distortions of cylindrical shape of the loop $(m > 1)$ remain unstabilized. It can be shown by theoretical analysis, however, that these need not lead to a displacement of the plasma loop with respect to its equilibrium position. In a toroidal system a conducting wall is used in order to contain the current loop, which tends to expand under the influence of the electromagnetic repulsive forces.

The method of stabilization indicated above has a number of advantages; in particular, the pinch stability for $m = 1$ is independent of the distribution of current over the cross section and it is not necessary that the current flow in a thin skin layer. As is shown by theory,[1] for a given value of the current J a plasma loop in a strong longitudinal magnetic field (not interacting with the walls of the chamber) can be heated to a much higher temperature than a toroidal system which is stabilized by a trapped "paramagnetic" field.

We write Eq. (1) in the form:

$$H_0 / (2J / ca) = kR / a, \tag{2}$$

where k is the stability coefficient. Then

$$k = ca^2 H_0 / 2RJ. \tag{3}$$

One of the problems of an experimental investigation of stabilization is that of studying the stability of a plasma loop as a function of k.

2. EXPERIMENTAL ARRANGEMENT. METHOD OF MEASUREMENT

The experiments to be described here have been carried out on a system called "Tokomak," which is a thick-walled copper toroid with a major diameter of 125 cm and a minor diameter of 50 cm, inside which is installed a short-circuit chamber made of stainless steel (wall thickness 0.1 mm). The space between the copper chamber and the inner chamber is evacuated to a pressure of 1×10^{-5} mm Hg. The pressure of the residual gases in the operating chamber is 1 to 2×10^{-6} mm Hg.

The design of the experimental apparatus is due to V. S. Vasil'evskiĭ and his colleagues.

The capacitor bank is discharged through the 19-turn primary winding of an air transformer, inducing a voltage in the toroid circuit and exciting the discharge. A quarter oscillation period for this voltage varies from 1.5 to 3 μsec depending on experimental conditions. The magnetic field in the operating chamber is produced by a coil which is wound on the toroid. This coil is excited by discharging a capacitor bank with a capacity of 0.1 farad at a maximum voltage of 5 kv. The half

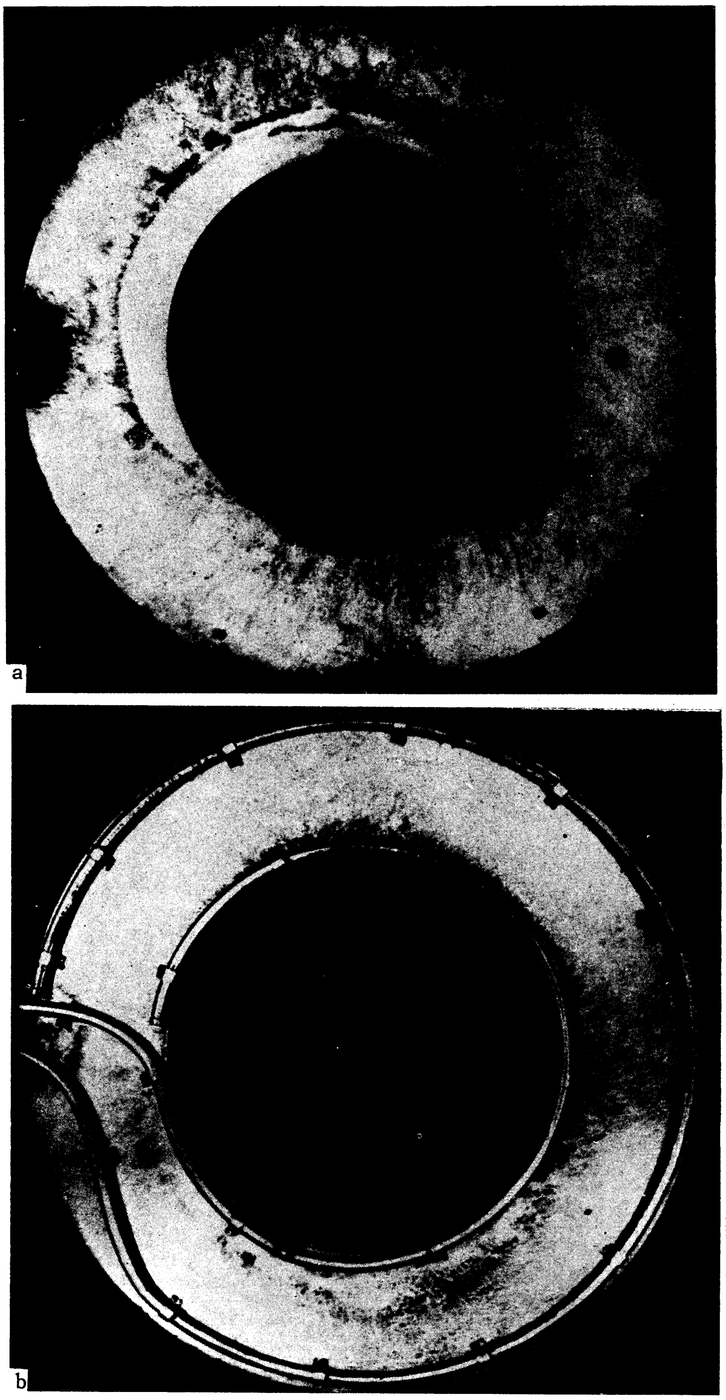

FIG. 1. The diaphragm (which defines the discharge) after several hundred pulses. a) The trace of the ion beam is displaced toward the outer wall of the toroid and upward from the equatorial plane, b) measuring loops on the diaphragm.

period for the magnetic field is 80 μsec. In the present experiments the strength of the longitudinal magnetic field H_0 could be varied from 600 to 12,000 oe. The initial intensity of the electric field along the axis of the chamber could be varied from 0.2 to 0.6 v/cm. The power supply for the system has been described in reference 3.

The work described here has been carried out at pressures ranging from 2×10^{-4} to 5×10^{-3} mm Hg and the operating gases which have been investigated include deuterium, argon and helium.

In order to produce a pinch which remains isolated from the walls of the chamber, thereby reducing the interaction with the walls, the chamber is provided with two diaphragms made of stainless steel 2 mm thick. In the first experiments the apertures in the diaphragms were 26 cm in diameter and the centers of the apertures were on the axis of the toroidal tube.

As is well known, the equilibrium position of a plasma loop in a toroid is displaced with respect to the axis. The photograph in Fig. 1 shows a diaphragm which was removed from the chamber after several hundred pulses. The plasma loop was displaced toward the outer wall of the chamber and upward. The displacement in the equatorial plane agrees with the calculated displacement. The displacement in the upward direction may be a consequence of some magnetic asymmetry, possibly the effect of fringing fields which penetrate through spaces in the copper shell.

All the principal measurements were carried out with diaphragms in which the apertures were displaced with respect to the axis in accordance with the experimentally determined position of the loop. These diaphragms are furnished with windings. By energizing the diaphragm windings it is possible to change the magnitude and direction of the longitudinal field in regions close to the diaphragms.

On each of the two diaphragms there are two Rogowsky loops. The loops are enclosed in thin-walled tubes of stainless steel. The wall thickness is chosen so that frequencies up to 200 kc are not attenuated. One of these loops is used to measure the current J_g which flows through the apertures in the diaphragm while the other is used to measure the current J_{g+d} which flows through the entire inner cross section of the chamber. In addition, there is a loop which is used to measure the total current J_{tot} which flows in the chamber (including the current in the shell of the inner chamber). By connecting the first and second loops in opposition we measure the current to the diaphragm $J_d = J_{g+d} - J_g$. By measuring the emf in the loop directly we measure the derivative of the current, dJ_g/dt. The loop voltage of the discharge chamber is measured, in the conventional way, by a loop in the equatorial plane of the toroid.

In addition to measuring its electrical characteristics, we investigate other properties of the plasma loop. Streak photographs of the optical radiation of the discharge in the visible region of the spectrum are also taken. A high-speed camera is used for this purpose.

The discharge radiation spectrum is studied with a DFS-6 vacuum spectrometer which is designed (according to its specifications) for the wavelength range between 60 and 2200 A. The time variation of the intensity of the individual spectral lines from deuterium and the impurities is studied by means of a ZMR-3 monochromator which is furnished with an electron photomultiplier at the output slit. The electron concentration in the plasma is estimated by the absorption of microwave radiation (73,000 and 130,000 Mcs). The measurement system is conventional and has been described, for example, in reference 3.

3. RESULTS OF THE MEASUREMENTS

The most interesting results are found in the streak photographs of the pinch. In Fig. 2 are shown streak photographs of a discharge in argon taken with $k_0 = 0.67$, 2.35, and 6.4, where

$$k_0 = ca^2 H_0 / 2R\,(J_r)_{max}.$$

It is apparent from Fig. 2a that the pinch is unstable. The luminous region reaches the diaphragm approximately 100 μsec after the discharge is initiated; after 300 μsec the plasma loop moves beyond the limits defined by the aperture in the diaphragm. The photograph shown in Fig. 2b indicates uniform luminosity, and the absence of any marked distortion of the pinch. The photograph in 2c is characterized by uniform luminosity and by the fact the luminosity over the entire cross section of the chamber grows weaker for 600 μsec. In all photographs the radiation is intense in the upper part of the chamber. It is more than likely that this effect

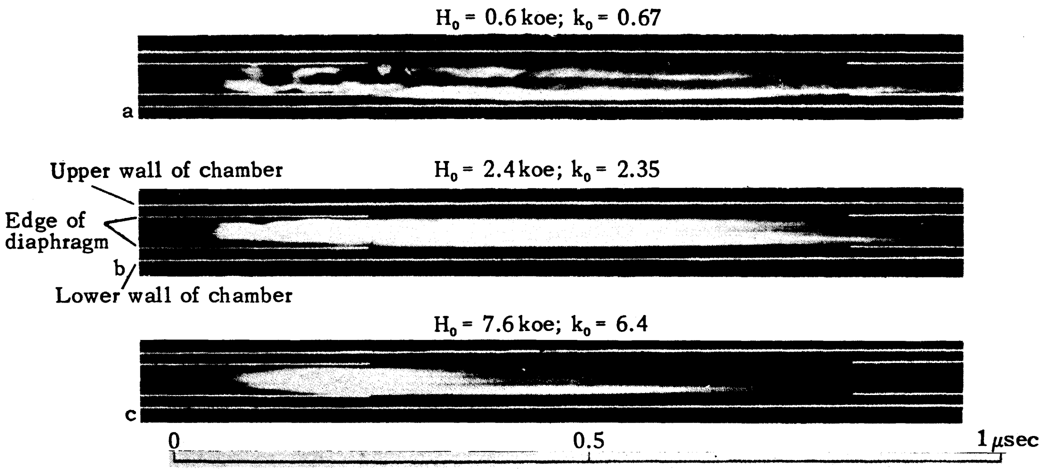

FIG. 2. Streak photographs of a plasma loop limited by diaphragms for different values of H_0 and k_0. The diaphragms are located at distances of 50 and 150 cm along the axis from the window through which the photographs are taken; $p = 10^{-3}$ mm hg (Ar).

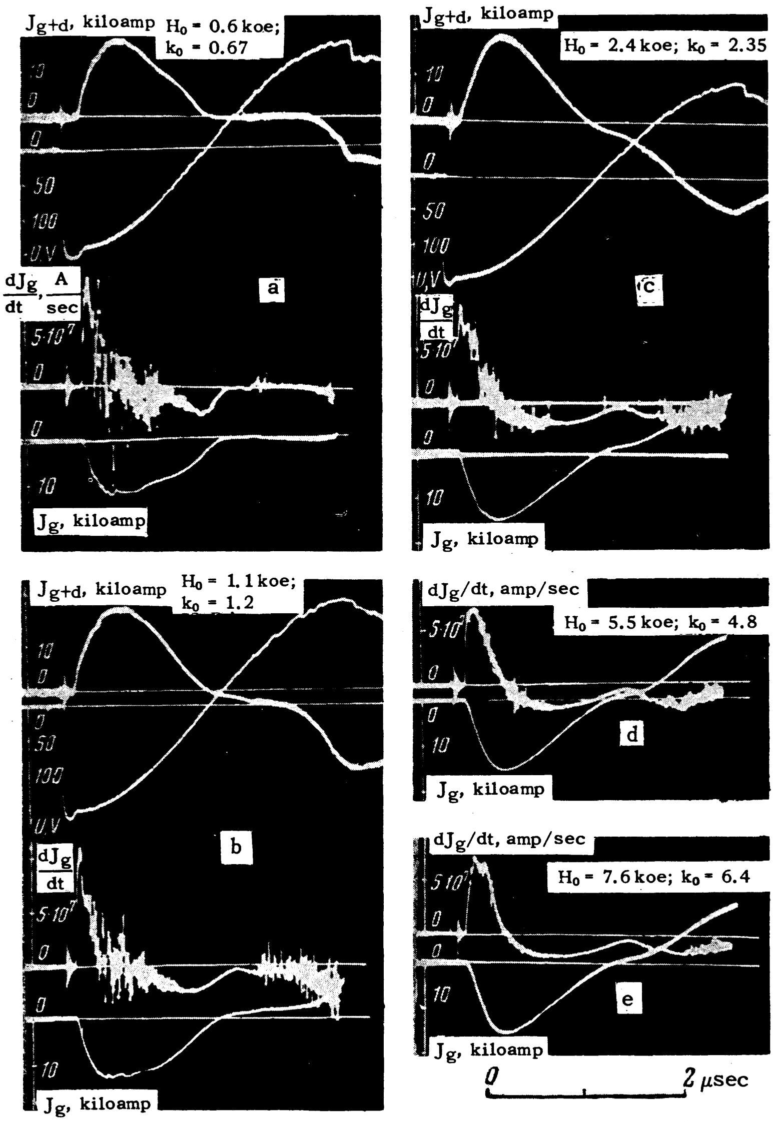

FIG. 3. Oscillograms showing the current J_{g+d}, the loop voltage U, the derivative of the current in the gas dJ_g/dt, and the current in the gas J_g for several values of k_0 (the gas is argon and $p_0 = 10^{-3}$ mm Hg).

is due to the fact that the apertures in the diaphragms and the equilibrium position of the toroidal loop are not exactly in coincidence.

The photographs of the discharge in deuterium are similar to those shown in Fig. 2. However, because of the low intensity of the radiation the films were not exposed completely.

It is interesting to compare these photographs with the other experimental data. In Fig. 3 are shown oscillograms of the current J_{g+d} and the loop voltage U, the derivative of the current in the gas dJ_g/dt, and the current in the gas J_g, all for argon. Oscillograms 3a, 4c, and 4e were obtained under the same conditions of operation as the photographs of the plasma loop.

On the oscillograms showing the current and the current derivative there are characteristic features that occur at the same instant of time. The J_g curve exhibits a discontinuity, indicating a considerable increase in current, while the current derivative dJ_g/dt falls off sharply; simultaneously, oscillations appear on the derivative oscillogram. As k_0 is increased the oscillations in the current derivative are reduced in amplitude. These features on the oscillograms showing the current and the current derivative coincide in time with the appearance of the current at the diaphragm J_d. This coincidence is seen from a comparison of the oscillograms for J_g and J_{g+d} and a careful examination of the current J_d.

A similar pattern is observed in the oscillograms obtained with a deuterium discharge. Typical oscillograms are shown in Fig. 4 for purposes of illustration.

The effect of the coefficient k_0, which characterizes the excess stability of the loop, can be illustrated by oscillograms which show the variation in time of the intensity of the deuterium spectral line D_β ($\lambda = 4860$ A). Such oscillograms are shown in Fig. 5. In order to relate the intensity of

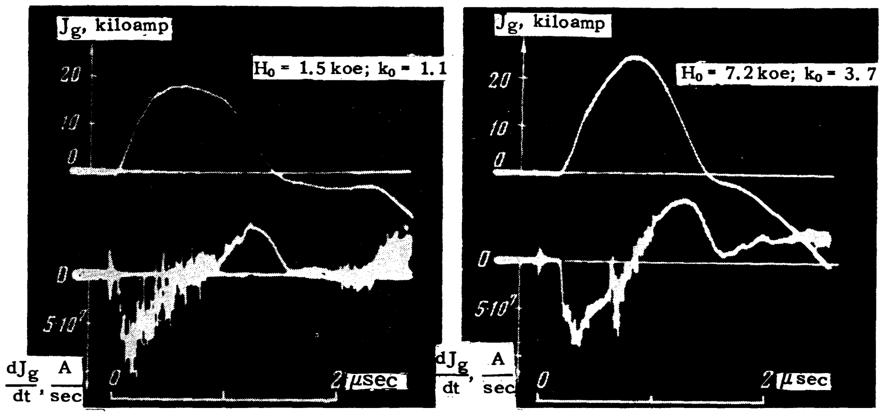

FIG. 4. Oscillograms of the current J_g and its derivative dJ_g/dt for two values of k_0 (the operating gas is deuterium and $p_0 = 10^{-3}$ mm Hg; $E_0 = 0.41$ v/cm).

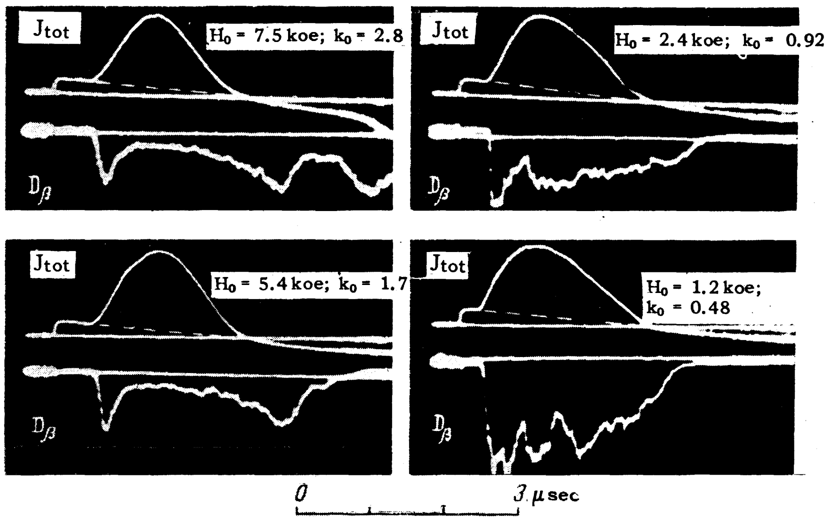

FIG. 5. Oscillograms showing the time variation of the intensity of the deuterium spectral line (D_β, $\lambda = 4860$ A) for various values of k_0 ($p_0 = 50 \times 10^{-4}$ mm Hg and $E_0 = 0.4$ v/cm).

the spectral line with the development of the discharge the upper beam of the oscilloscope is used to display the total chamber current J_{tot}. The small current at the beginning of the process is the current in the inner short-circuit chamber.

With $k_0 = 2.8$ and 1.7, after breakdown of the gas the intensity of the D_β line first increases sharply, reaching a maximum in approximately 50 μsec. It then falls off for 300 — 400 μsec, after which some increase is observed. With a reduction in excess stability the picture changes markedly. When $k_0 < 1$ there the intensity fluctuates widely as long as current flows in the gas. When a strong magnetic field is used the intensity of the D_β line remains high one microsecond after the flow of current in the gas is terminated. As H_0 is reduced this time period is also reduced.

In Figs. 6a and b are shown oscillograms for the currents J_{g+d} and J_g, the current derivative dJ_g/dt, the loop voltage U, the intensity of the deuterium D_β line, and the current to the diaphragm J_d for two values of k_0. Under the oscillograms (same time scale) is shown the mean electrical conductivity (over the cross section of the pinch) σ during the discharge. The electrical conductivity is computed from the formula

$$\sigma = 9 \cdot 10^{11} \frac{2RJ_g}{a^2(U_{loop} - L_p dJ_g/dt)} \text{ [cgs esu]},$$

where L_p is the inductance of the pinch, which is assumed to be constant and given by $L_p = 4\sigma R \times \ln(b/a)$ (b is the radius of the shielding shell).

Comparing the oscillograms of the current to the diaphragm with the other oscillograms, we see that the time at which the intensity of the D_β line stops diminishing corresponds to the time at which the current to the diaphragm appears. At the same time the current derivative increases for a period estimated as 30 — 50 μsec. At approximately the same instant of time the conductivity of the plasma starts to drop.

In Fig. 7 are shown oscillograms of the C III line (doubly charged carbon, $\lambda = 4651$ A) which are synchronized with the oscillograms showing the diaphragm current. As the intensity of the longitudi-

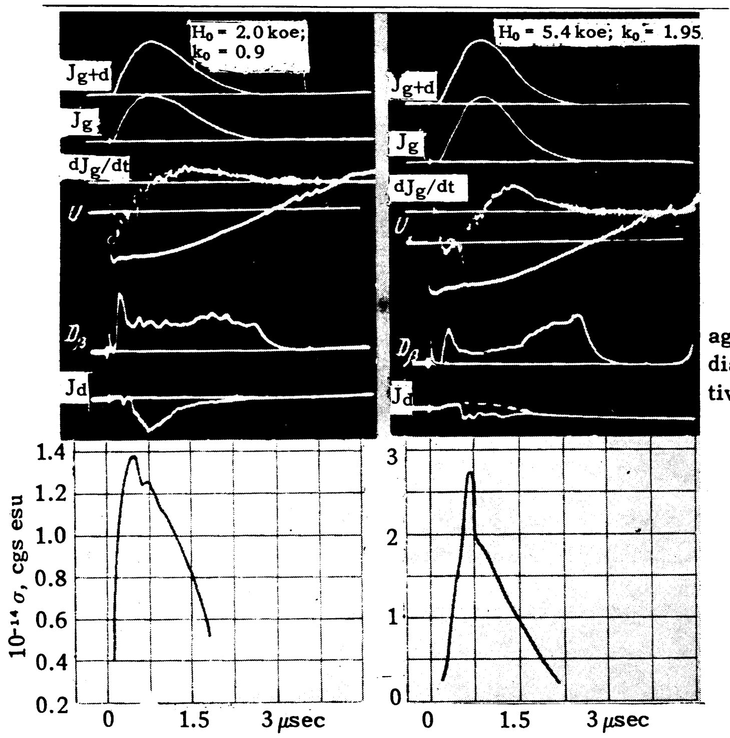

FIG. 6. Oscillograms showing the currents, loop voltage, intensity of the deuterium spectral line, current to the diaphragm and the calculated value of the electrical conductivity of the plasma loop ($p_0 = 10^{-3}$ mm Hg; $E_0 = 0.43$ v/cm).

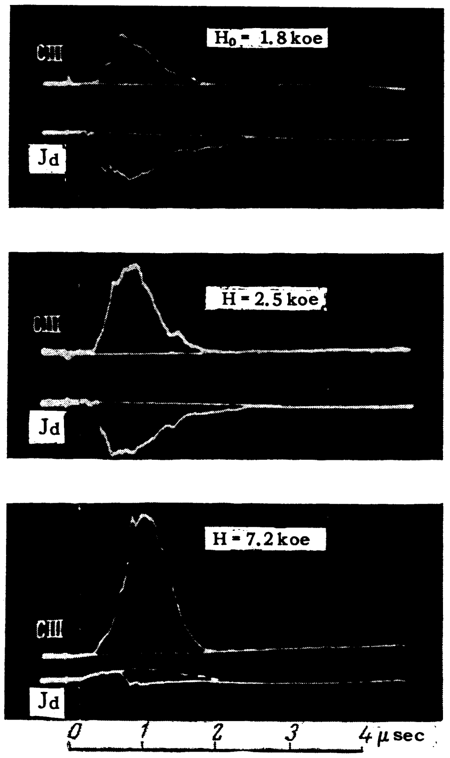

FIG. 7. Oscillograms showing the intensity of the spectral line C III ($\lambda = 4651$ A) and the current to the diaphragm for three values of the longitudinal magnetic field. Discharge in deuterium ($p_0 = 10^{-3}$ mm Hg, $E_0 = 0.43$ v/cm).

nal magnetic field H_0 is increased, the intensity of this line also increases.

A number of tests have been made to investigate the role of impurities in the operating gas in processes by which energy is lost from the plasma. In Fig. 8 are shown the relative intensities of the lines on the discharge spectrogram taken with the DFS-6 vacuum spectrometer. This spectrogram represents 150 pulses in stable operation for ($k_0 > 1$).

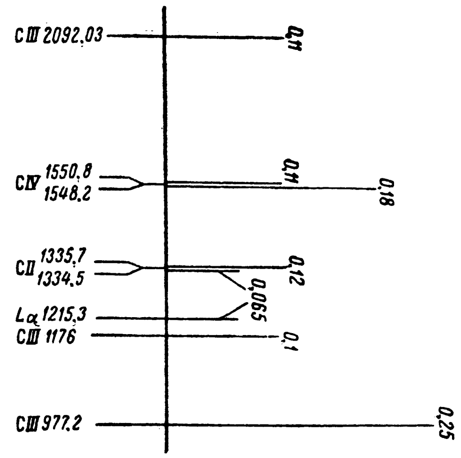

FIG. 8. Relative intensities of the lines on the discharge spectrum taken for 150 pulses with E = 0.42 v/cm and H_0 = 7200 oe; the deuterium pressure is $p = 10^{-3}$ mm Hg.

The photograph film was sensitized by sodium salicylate, which has a uniform quantum yield for wavelengths between 600 and 3,000 A.[4] An exposure of 150 pulses provides normal blackening for the most intense lines L_α ($\lambda = 1215.3$ A) and C III ($\lambda = 1176$ A). On the spectrogram only the lines for deuterium and carbon were measured. In Fig. 8 the vertical lines indicate the relative energies in the different spectral lines. The total energy of all the lines in the spectrogram is taken as unity. It is apparent that the radiation from deuterium is only $^1/_{15}$ to $^1/_{20}$ of the total energy radiated in this region of the spectrum.

A rough estimate of the absolute magnitude of the radiation loss is given by the following experiment. A photographic film, which is first calibrated by means of a thermocouple, is placed in an auxilliary section, which connects to the discharge chamber. The film is sensitized with sodium salicylate. One-third of the film is covered by a glass filter, another third by a quartz filter, and part of the film is left completely exposed. From the blackening of the film we determine the absolute and relative radiation energy emitted in various portions of the spectrum. Preliminary measurements indicate that only 5% of the total energy emitted by the plasma is contained in the visible and near ultraviolet; most of the energy (up to 50%) is emitted as hard radiation.

The electron concentration in the plasma is determined by microwave probing. At a frequency of 130,000 Mcs microwave radiation is transmitted for 400 to 500 μsec after current starts to flow in the gas. After this period the microwave radiation is completely attenuated. Thus, the electron density is at least 2.5×10^{14} cm^{-3}. Furthermore, the measurements indicate that the electron concentration remains large for one microsecond after the discharge is extinguished. This result is in agreement with the data given for the D_β line for this same time period.

4. DISCUSSION OF THE RESULTS AND CONCLUSIONS

A. Stability. In Fig. 9 the ratio of diaphragm current to gas current (J_d/J_g) is plotted as a function of k_0 from an analysis of the oscillograms; the currents J_d and J_g are taken for times corresponding to the maximum value of the gas current. When $k_0 < 1$ this ratio falls off rapidly with increasing k_0. When $k_0 > 1$ this ratio continues to fall off, but at a much slower rate.*

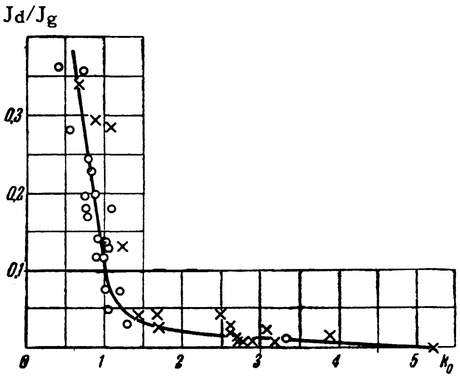

FIG. 9. The ratio of the diaphragm current J_d to the gas current J_g as a function of k_0 for two series of experiments (the gas is deuterium).

The break in the curve which is observed at values of k_0 close to unity indicates the existence of a critical current which characterizes the boundary between stable and unstable states of the plasma loop. The critical current can be estimated as follows:

$$J_{cr} = ca^2 H_0 / 2R.$$

For operating conditions characterized by $J_{max} > J_{cr}$, i.e., $k_0 > 1$, at the beginning of the discharge the gas current is less than the critical value and the pinch is stable. Later the gas current increases, reaching the critical value when $k_0 = 1$. At this point the pinch becomes unstable and there is a large current to the diaphragm. In Fig. 10 the points indicate the values of the gas current J_g at times corresponding to the appearance of the diaphragm current for discharges characterized by $J_{max} > J_{cr}$ for various values of the longitudinal magnetic field H_0. The dashed line shows the calculated value of the critical current. Functional relations of this kind are also found for discharges in helium and argon.

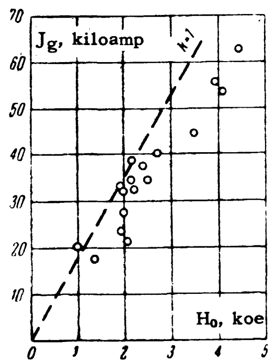

FIG. 10. The gas current J_g as a function of magnetic field at the time corresponding to the appearance of current to the diaphragm. The dashed line is the value calculated for $k = 1$.

When $k_0 > 1$ the current to the diaphragm falls off as k_0 increases; however, higher values of k_0 could not be achieved because the longitudinal magnetic field could not be increased. It is not very fruitful to increase k_0 by reducing the gas current because the energy evolved per pulse becomes small and, under certain conditions, can become smaller than that required for dissociation and ionization of the gas in the chamber. In the pres-

*The dependence is somewhat different when the centers of the apertures in the diaphragms coincide with the axis of the toroidal tube [Report by M. A. Leontovich at the Harwell Research Establishment (Great Britain), April, 1959]. When $k_0 > 1$ considerable current to the diaphragm is observed because the apertures in the diaphragms are not in coincidence with the equilibrium position of the plasma loop in the toroid.

ent experiments, with $k_0 = 5$ the current to the diaphragm was too small to be detected by the measuring apparatus.

The measurements of the intensity of the D_β line also illustrate the effect of the longitudinal magnetic field on plasma stability. For $k_0 < 1$, when the discharge current is greater than the critical value the intensity of the D_β line is higher than for $k_0 > 1$ and varies at random. It is possible that this behavior is a consequence of kinks in the plasma loop, which lead to a strong interaction with the diaphragm and perhaps with the walls of the chamber. Under these conditions the plasma tends to de-ionize and neutral atoms are excited a second time. At high magnetic fields ($k_0 > 1$) the oscillograms showing the intensity of the D_β line are regular and can be reproduced from discharge to discharge.

B. Ionization. The data available to us are inadequate for determining the concentration of charged particles in the plasma loop.

From the results of microwave probing of the plasma it follows that the concentration of electrons in the plasma loop is at least 1.5 times greater than the initial concentration of deuterium atoms. It is possible that the increase in electron concentration is a consequence of ionization of impurity atoms or deuterium atoms which enter the plasma loop from peripheral regions.

As is indicated by the data which have been presented, the electrical conductivity (averaged over the cross section of the plasma loop) increases for some time after the intensity of the D_β line starts to diminish. This result can be interpreted assuming that ionization of most of the neutral gas is terminated. Hence, it does not contradict the results obtained by microwave probing of the plasma. The increase in electrical conductivity after ionization is terminated is apparently due to heating of the plasma.

The high degree of ionization is indicated by the fact that the discharge spectrum contains intense lines due to doubly charged (C III) and triply charged (C IV) carbon. The corresponding ionization potentials are 22.28 v and 47.55 v. Thus, the plasma contains electrons with energies several times greater than the ionization potential of deuterium.

Finally, we can cite the data obtained by a microphotometric analysis of the films used in the streak photographs of the pinch. An analysis of these data, which takes account of the geometric factors, indicates that the radiation in the center of the pinch is less intense than the radiation from the outer layer. In all probability, the outer layer of the plasma, which is in contact with a layer of neutral particles, radiates a great part of the energy in the visible portion of the spectrum. Rough probe measurements indicate a sharp drop in the concentration of charged particles as a function of distance from the axis of the plasma loop. It follows from these measurements that the concentration of charged particles at the walls of the chamber is no greater than 10^{11} particles/cm^3.

C. Electron temperature. As is well known, the electron temperature in a fully ionized plasma, T_e, can be determined from the electrical conductivity σ. Thus, on the basis of the usual relations, it is found that the mean electron temperature $T_e \sim 7$ ev if the mean conductivity as averaged over the cross section of the plasma loop is $2-3 \times 10^{14}$ cgs esu. If we estimate T_e from the relative intensities of the impurity lines (in the present case, C I, C II, etc.) the electron temperature is found to be approximately 15 ev.

It has been noted above that the diaphragms located in the chamber are furnished with windings. Current pulses from a condenser bank can be applied to these windings. When this is done the current to the diaphragms is reduced but the total gas current J_g is increased. Under certain conditions the current increases by a factor of $1.4-1.5$. The loop voltage does not change under these conditions. It is more than likely that the increase in current is due to the increase in the cross section of the pinch over the entire chamber because of the deformation of the lines of force in the longitudinal field.

The following conclusions may be drawn from the data reported here.

1. A plasma loop formed in a toroidal chamber in the presence of a longitudinal magnetic field is stable when $k > 1$ and unstable when $k < 1$.

2. The equilibrium position of a plasma loop in a toroidal chamber is determined with a fair degree of accuracy by theory. Certain distortions in the equilibrium orbit found in the present experiments are apparently to be associated with the construction of the chamber.

3. The degree of ionization achieved in these experiments is rather high; the gas is almost completely ionized.

4. The temperature of the electrons in the plasma is not greater than 15 ev in spite of the fact that the amount of energy which goes into the plasma is sufficient to heat the electrons to a higher temperature. A measurement of the radiation losses indicates that impurity atoms are responsible for a considerable portion of the energy loss.

The authors wish to acknowledge the continued attention and useful discussions which have been contributed to the present work by L. A. Artsimovich. They also wish to express their gratitude to their colleagues Yu. A. Gusev and G. A. Egorenkov.

[1] S. I. Braginskiĭ and V. D. Shafranov, Nuclear Physics, Report of Soviet Delegation to 2nd International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958, Glavatom, 1959 p. 221.

[2] V. D. Shafranov, Атомная энергия (Atomic Energy) **5**, 38 (1956).

[3] Dolgov-Savel'ev, Ivanov, Mukhovatov, Razumova, Strelkov, Shepelev, and Yavlenskiĭ, loc. cit. ref. 1, p. 85.

[4] Watanabe, Edward, and Inn, J. Opt. Soc. Am. **43**, 32 (1953).

Translated by H. Lashinsky
88

ERRATA TO VOLUME 10

page	reads	should read
Article by A. S. Khaĭkin		
1044, title	. . . resonance in lead	. . . resonance in tin
6th line of article	~ 1000 oe	~ 1 oe
Article by V. L. Lyuboshitz		
1223, Eq. (13), second line	$\ldots - \mathrm{Sp}_{1,2}\mathscr{E}(\mathbf{e}_1)$	$\ldots - \mathrm{Sp}_{1,2}\mathscr{E}(\mathbf{e}_2)\ldots$
1226, Eq. (26), 12th line	$\cdots\{(\mathbf{p}+\mathbf{q},\ \mathbf{p}$	$\cdots\{(\mathbf{p}+\mathbf{q},\mathbf{p}) - (\mathbf{p}+\mathbf{q},\ \mathbf{n})\cdot\cdot(\mathbf{pn})\}$
1227, Eqs. (38), (41), (41a) numerators and denominators	$(\mathbf{p}^2 - \mathbf{q})$	$(\mathbf{p}^2 - \mathbf{q}^2)^2$
1228, top line	$\mathbf{m}_2 = \frac{\mathbf{q}_1 - \mathbf{p}_1}{\mathbf{q}_1 - \mathbf{p}_1}$	$\mathbf{m}_2 = [\mathbf{m}_3\ \mathbf{m}_1]$

ERRATA TO VOLUME 12

page	reads	should read
Article by Dzhelepov et al.		
205, figure caption	54	5.4
Article by M. Gavrila		
225, Eq. (2), last line	$-2\gamma\Theta^{-4}\,{}^1\!/_8$	$-2\gamma\Theta^{-4} - {}^1\!/_8$
Article by Dolgov-Savel'ev et al.		
291, caption of Fig. 5, 4th line	$p_0 = 50 \times 10^{-4}$ mm Hg	$p_0 = 5 \times 10^{-4}$ mm Hg.
Article by Belov et al.		
396, Eq. (24) second line	$\ldots - (4 - 2\eta)\,\sigma_1 + \ldots$	$\ldots + (4 - 2\eta)\,\sigma_1 + \ldots$
396, 17th line (r) from top	. . less than 0.7	. . less than 0.07
Article by Kovrizhnykh and Rukhadze		
615, 1st line after Eq. (1)	$\omega_{0e}^2 = 2\pi e^2 n_e/m_e$,	$\omega_{0e}^2 = 4\pi e^2 n_e/m_e$,
Article by Belyaev et al.		
686, Eq. (1), 4th line	$\ldots b_{\rho_2 m_2}(s_2') + \cdots$	$\ldots b_{\rho_1 m_1}(s_1') + \cdots$
Article by Zinov and Korenchenko		
798, Table X, heading of last column	$\sigma_{\pi^- \to \pi^+} =$	$\sigma_{\pi^- \to \pi^-} =$
Article by V. M. Shekhter		
967, 3d line after Eq. (3)	$\varepsilon \equiv 2m_pE + m_p^2$	$\varepsilon \equiv (2m_pE + m_p^2)^{1/2}$
967, Eq. (5), line 2	$+ (B_V^2 + B_A^2)\ldots$	$+ (B_V^2 + B_A^2)\,Q\ldots$
968, Eq. (7)	$\ldots(C_V^2 + C_A^2)$.	$\ldots C_V^2 + C_A^2 - Q^2(B_V^2 + B_A^2)$.
968, line after Eq. (7)	for $C_V^2 + C_A^2 \equiv \ldots$	for $C_V^2 + C_A^2 - Q^2(B_V^2 + B_A^2) \equiv \ldots$
Article by Dovzhenko et al.		
983, 11th line (r)	$\gamma = 1.8 \pm$	$\gamma = 1{,}8 \pm 0{,}2$
Article by Zinov et al.		
1021, Table XI, col. 4	$-1{,}22$	$1{,}22$
Article by V. I. Ritus		
1079, line 27 (l)	$-\Lambda_{\pm}(t)$,	$\Lambda_{\pm}(t)$,
1079, first line after Eq. (33)	$\frac{1}{2}(1 + \beta)$.	$\frac{1}{2}(1 \pm \beta)$.
1079, 3d line (l) from bottom	$\ldots\mathfrak{N}(q'p;\ pq')\ldots$	$\ldots\mathfrak{N}(p'q;\ pq')\ldots$
Article by R. V. Polovin		
1119, Eq. (8.2), fourth line	$U_{0x}u_xg(\gamma) - [\gamma\cdots$	$-U_{0x}u_xg(\gamma)\,[\gamma\ldots$
1119, Eq. (8.3)	$\cdots$sign u.	$\cdots$sign u_g.
Article by V. P. Silin		
1138, Eq. (18)	$\cdots + \frac{4}{5}c^2k^2$	$\cdots + \frac{6}{5}c^2k^2$.