Deformation of Arc Column in Rarefied Gases at High Currents*

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Various phenomena occurring in the arc of Hg, H_2, Ar and Kr at $p \sim 10^{-4} - 10^{-3}$ mm Hg and currents i_a up to 2000 amp were studied. By the method of a movable probe it was found that the half-width of the arc column decreases by 30% when the current i_a increases up to 10^2 amp. A further increase in current gives rise to gradually increasing vibrations first in the probe current, then in the arc voltage and finally, in the arc current, with an average frequency $f = 10^4 - 10^5$ cycles. The oscillograms of the current on two identical and symmetrically located probes show that these vibrations may be interpreted as the result of irregular propagation of the compressed arc column along the cross section of the tube. At current pulses $i_a \sim 500 - 2000$ amp with a duration of 1-10 μsec, it is possible to observe the compressed arc column visually and photographically; the column is found to be compressed into a narrow cord, curved into a helix and pressed against the walls of the tube. With the aid of a rotating photo-camera it was shown that, at prolonged ($10^2 - 10^3$ μsec) current pulses, the arc is also compressed and is repeatedly propagated along the cross section of the tube. The compression and the curvature of the arc column are of electrodynamic origin, but its propagation is of gasodynamic origin.

1. INTRODUCTION

THE passage of a strong electric current in a rarefied gas is accompanied by a number of specific phenomena which are not noticeable at lower currents. In particular, it was pointed out repeatedly that at high currents there should occur transverse compression in the flow of charge carriers under the action of the self-magnetic field[1,2].

The quantitative theory developed by Tonks led to the conclusion that, upon approaching the critical current $i_{cr}(a) \approx 6 \times 10^5 T_e^{3/2}(^\circ\mathrm{K})/\lambda_e(\mathrm{cm}) \times E(V/\mathrm{cm})$, the current density at the axis should increase without limit. An assumption was proposed that such compression of the current into a narrow cord should be accompanied by a strong rarefication of the gas in this cord; the consequence of this simultaneous increase in the current density and of the drop in the density of the substance would result in a break in the current (pinch effect). A number of investigations have been devoted to the further development of the theory of this phenomenon[3,4].

Several attempts were also made to detect experimentally the electrodynamic compression of the arc column in a rarefied gas. With the aid of probes, the arc was studied in mercury vapor at currents up to 150 amp and at a vapor pressure $p = 10^{-1} - 10^{+1}\,\mu$Hg and up to 80 amp at $p = 2\,\mu$Hg[5]. It was found that at $i_a = 50$ amp and $p = 0.5\,\mu$Hg, the radial electric field is almost nonexistent; apparently, the electron distribution along the cross section of the tube is determined mainly by the magnetic field, which replaces the radial electric field of the arc column. The half-width of the concentration distribution is compressed by 27% at $i_a = 150$ amp[3] and by 20% at $i_a = 80$ amp[5]. Also, with the aid of probes[6] it was found that in the hydrogen arc at $p = 30\,\mu$Hg, the current distribution curves are compressed by 30% when the current increases from 20 to 102 amp. With a high-frequency nonelectrode (circular) current, there were observed in Kr and in other gases at $p < 0.5\,\mu$Hg and $i_a > 10^4$ amp (with the aid of a rotating camera) variations in the thickness of the luminous region, the frequency of which depends on the pressure, on the atomic weight of the gas and on the applied voltage[7]. The authors explain these variations as a manifestation of the

* Brief communication, see J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 378 (1955); Soviet Physics JETP **1**, 381 (1955).

[1] W.H. Bennett, Phys. Rev. **45**, 890 (1934).

[2] L. Tonks, Trans. Electrochem. Soc. **72**, 629 (1937); Phys. Rev. **56**, 360 (1939).

[3] P.C. Thonemann and W.T. Cowhig, Proc. Phys. Soc. (London) **64**, 345 (1951).

[4] M. Blackman, Proc. Phys. Soc. (London) **64**, 1039 (1951); A. Schlüter, Z. Naturforsch. **5a**, 72 (1950); M. Kruskal and M. Schwarzschild, Proc. Roy. Soc. (London) **223A**, 348 (1954).

[5] H. Fetz, Ann. Physik **40**, 570 (1941).

[6] B.A. Mamyrin, J. Tech. Phys. (U.S.S.R.) **25**, 1914 (1953).

[7] S.W. Cousins and A.A. Ware, Proc. Phys. Soc. (London) **64**, 159 (1951).

pinch effect. In the arc channel in H_2, Ar and in air at atmospheric pressure and at currents of the order of 10^5 amp, there are observed phenomena which the authors also interpret as the pinch effect[8].

We do not know of any descriptions of the considerable electrodynamic compression of the low pressure arc in simple cases, that is, at a current flowing in a single direction.

The object of the present investigation was first to establish the main fact: whether there occurs any noticeable compression in the arc of a constant, or slowly changing, current in a rarefied gas when the current is increased*. Should the answer be yes, then it would be necessary to answer 1) why this compression remained unnoticed, 2) how it can be explained, 3) whether it leads to a break in the current as predicted by the Tonks hypothesis.

2. EXPERIMENTAL PROCEDURE AND APPARATUS

In carrying out the experiment, we have used cylindrical tubes having a length of l = 100-500 mm and a diameter of $2R$ = 10-70 mm; in all cases $l \gg 2R$. We have avoided any kind of constrictions in the tubes, since the presence of constrictions introduces new factors (double electrical layer in front of the constriction) and may lead to instability and a break in the current[2, 9]. With a small diameter of the main section of the tube, which of necessity has to be much narrower than the cathode section, the transition between these was very gradual and even.

The tubes were filled with Hg, H_2, Ar and Kr. In the experiments with Hg, a liquid mercury cathode was used. In order to avoid the flow of vapor from the cathode into the section of the arc under investigation (positive column), the tube was bent (Fig. 1*a*) and a screen (reflector) for the mercury vapor was placed over the cathode. The gap between the screen and the walls remained sufficiently wide so as not to cause any narrowing of the tube. For the control of the vapor pressure in the tube, the whole cathode section was submerged into water.

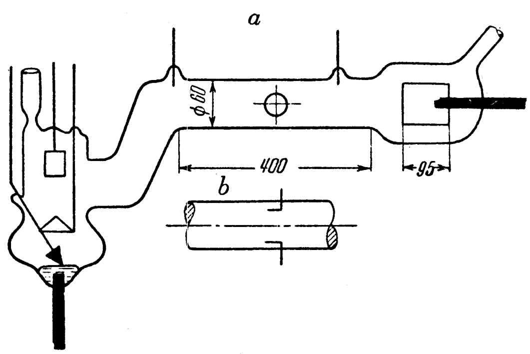


FIG. 1. *a*--mercury tube, *b*--arrangement of the two symmetrical probes with respect to the axis of the tube.

In the experiments with the other gases a copper cathode of finely cut pieces of copper wire was used instead of the mercury cathode. Since the flow of vapor from the copper cathode is not significant, these tubes were made straight (Fig. 2), without any screens and without water cooling.

The arc was excited in both types of tubes by means of a semi-conductive igniter*, submerged into mercury or copper. Cylindrical tungsten probes with a diameter of 0.5 mm were introduced

* At a high gas pressure contraction (compression) of the column always occurs, but for another reason (a drop in the temperature of the gas from the axis to the periphery of the column); therefore, the electrodynamic effect here is superimposed on the ordinary contraction and it is not easy to separate it in this case[8].

[8] J.E. Allen and J.D. Craggs, Brit. J. Appl. Phys. **65**, 446 (1954).

* The igniters were supplied by the laboratory of defense apparatus of VEI (All-Union Electrical Engineering Institute).

[9] A.W. Hull, Electr. Eng. **53**, 1435 (1934); H. Kleinwachter, Arch. Elektrotechn. **34**, 523 (1940); B.N. Kliarfeld and I.A. Poletaev, Dokl. Akad. Nauk SSSR **23**, 460 (1939); V.L. Granovskii and T.A. Suetin, J. Tech. Phys. (U.S.S.R.) **16**, 1023 (1946).

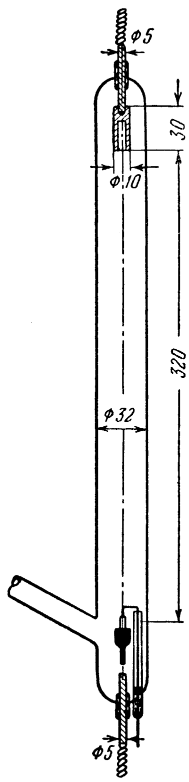


FIG. 2. Tube used in the experiments with H_2 and with inert gases.

into the anode arm of the tube, their working portion being parallel to the axis of the tube, and the remaining part being coated with fused quartz. The study of the current distribution along the cross section was carried out by a probe, movable along the diameter of the tube by an iron anchor, of the external coil and of the control apparatus. In one series of experiments (see below, section 3b), two identical probes were introduced into the tube; these were placed symmetrically with respect to the tube axis and at a distance of 10 mm from it (see Fig. 1*b*). The probes were supplied with the voltage $U_p = -60$V with respect to the cathode, this ensured a purely ionic current to the probe. Under the conditions of our investigation we had to forego the measurement of the electronic currents and the determination from them of the electron concentrations, since the self-magnetic field of the arc current, approaching in these experiments 10^2 Oe, makes the interpretation of the electronic portions of the probe characteristics exceedingly difficult (see Ref. 10).

[10] G. L. Spivak and E.M. Reikhrudel, J. Exptl. Theoret Phys. (U.S.S.R.) **16**, 816 (1936).

Therefore, we concentrated on the determination of the ionic current in the probe i_p for one and the same voltage, which was sufficiently negative with respect to the cathode at various positions of the probe. The relative value of i_p at various points of the tube diameter provides the possibility of judging approximately the distribution of the ion concentration and, therefore, also of the electrons along the cross section of the column.

Sources of arc current in the various experiments were: circuit of constant current, transformers and pulse circuits. In the first case, a constant current was passed through the tube. In the second case, a single igniting pulse was passed through the igniter, which caused the passage through the tube of a single half-wave of current $f = 50$ cycles. In the third case, the discharge through the tube of a charged condenser was also produced by a pulse igniter. The resultant single current pulse in one direction in the tube had a considerably smaller duration (1-50 μsec).

The recording and the measurement of the electrical values, and first of all of the arc current and voltage i_a and U_a, and of the probe current i_p, were carried out by indicating instruments and by electronic oscillographs having electrical and mechanical resolution. The probe currents were measured with indicating instruments not only for a constant arc current, but also for single current pulses. In this case, the indicating instrument gave a ballistic reading proportional to $\int_0^T i_p dt$. The readings thus obtained were compared with each other for various conditions, for example, for various positions of the probe with respect to the axis. In addition, the probe currents, as well as the current and voltage of the arc, were oscillographed. For this purpose, coaxial-cylindrical or doubly-wound resistances of low inductance were connected into the probe and the arc circuits. In some cases, the voltage on these resistances was initially intensified by a constant current amplifier.

The external shape of the arc was photographed with an ordinary photo-camera. Owing to the comparatively low brightness of the arc at the pressures with which we were working, the photographing represented definite difficulties, particularly for the short-current pulses. It was not always possible to overcome these difficulties, even when we used a film with a sensitivity up to 250 units GOST.

For the observation of transverse compression and propagation of the arc at long current pulses a single transverse section of the arc was photographed and resolved. For this purpose, a double screen having slits perpendicular to the axis of the tube was placed in front of the arc (Fig. 3). An image was reflected by a Zonnar objective 1:1.5; $F = 50$ mm on the photo-film of the rotating camera having a screen with a diameter of 300 mm and a number of revolutions up to 200 sec^{-1}.

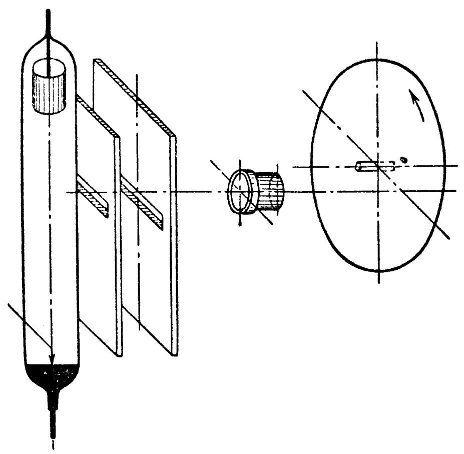


FIG. 3. Diagram for the observation of arc propagation.

3. EXPERIMENTAL RESULTS

a) Probe measurements of the distribution of charge carriers along the cross section of the tube.

We carried out these measurements with the aid of a movable probe in a tube $R = 35$ mm in mercury vapor at i_a from 13 to 1700 amp. The probe currents were determined with an indicating instrument, as well as with an oscillograph. The final form of the readings at $i_a \geq 1000$ amp was complicated by strong vibrations of the ionic current. In these cases, the average value $i_p = \frac{1}{T}\int_0^T i_p dt$ was determined. Readings were taken at 14 different positions of the probe, that is, every 5 mm. These were divided by the maximum reading of the given series, generally otbained near the axis of the tube. The ratios $i_p(r)/(i_p)_{max}$ or $\int i_p(r)dt/\int(i_p)_{max}dt$ thus obtained, expressed as functions of r/R, may characterize the distribution of the charge carriers along the cross section of the tube. The parameter characterizing the degree of arc compression may be the relative half-width of the column $(r/R)_{1/2}$, that is, the value r/R at which $i_p(r)/(i_p)_{max} = 1/2$.

Table I gives the values which we found for $(r/R)_{1/2}$ of the mercury arc column at $R = 35$ mm, at various temperatures of Hg condensation and at various arc currents i_a. The data relating to i_a = 1amp were taken from old measurements[11].

TABLE I. Relative half-width $(r/R)_{1/2}$ of the arc column in Hg at various currents, determined with probes.

Temperature of Condensation °C	Saturated Vapor Pressure μHg	Arc Current in Amperes								Method of Determination
		1	22	50	85	170	680	1000	1700	
9	0.5	>1*				0.71		0.71	0.71	Oscillograph
16—17**	0.9÷1.0	~1	0.80	0.78	0.78					The Same
16—22**	0.9÷1.5	~1	0.77	0.77	0.74	0.71		0.71	0.77	Indicating Instrument
19—22**	1.2÷1.5	~1					0.71	0.66	0.75—0.78	Oscillograph

* At these conditions (n_e) column$/(n_e)_0 > 1/2$.

** Here the data of several measurements at somewhat different temperatures are taken together, since there was no great difference between them.

[11] V.L. Granovskii, *Symposium on Electronic and Ionic Apparatus*, State Energetics Press, Moscow, 1941, p. 122.

These results show that the arc compresses by approximately 30% when the current is increased up to ~ 170 amp. When the current was increased up to 1700 amp, it was not possible to observe any further compression the arc column by means of probe measurements.

b) Fluctuations of the arc parameters at high currents.

Irrespective of the fact that the results of probe observations described in Sec. a) are quite limited, the properties of the arc continued to change when the current was increased above 200 amp. This was indicated first by the large increase in the arc voltage U_a at high currents (Fig. 4), second by the resulting fluctuations (which increased with an increase in current) of all the

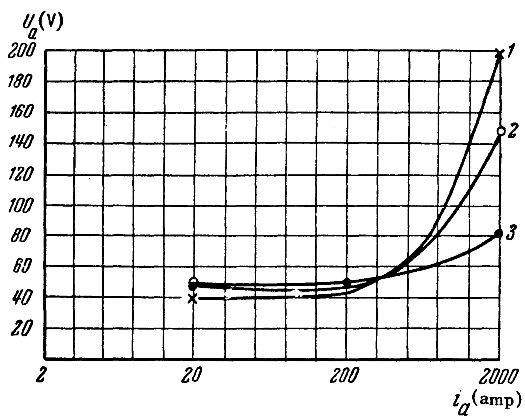


FIG. 4. The dependence of the arc voltage on the current in a cylindrical tube. 1--p = 1, 2--p = 10, 3--p = 100μHg.

parameters of the arc. A study of the oscillograms of the current i_a, of the arc voltage U_a, as well as of the probe current i_p, in a tube of diameter 60(70) mm in mercury vapor at pressures of 0.4 to 6 μHg when a single semi-sinusoidal current of 50 cycles is passed showed the following:

At a current up to 500 amp (current density $\bar{j}_a$ up to 12 amp/cm^2, averaged over the entire cross section of the tube) the arc is quite stable in the range of pressures investigated, the arc current and voltage (i_a and U_a), as well as the probe current i_p, do not experience any noticeable fluctuations (Fig. 5).

At i_a ~1000 amp (j_a~30 amp/cm^2), signs of instability in the arc column begin to appear. The

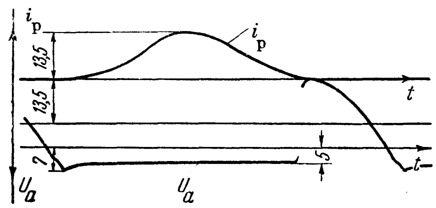


FIG. 5. The arc voltage U_a and the ionic current in the probe i_p when $(i_a)_{max}$ = 1.0 amp, p = 0.4 μHg.

arc voltage U_a (Fig. 6) and the probe current i_p (Fig. 7) experience irregular fluctuations about

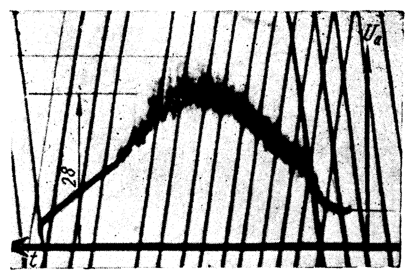
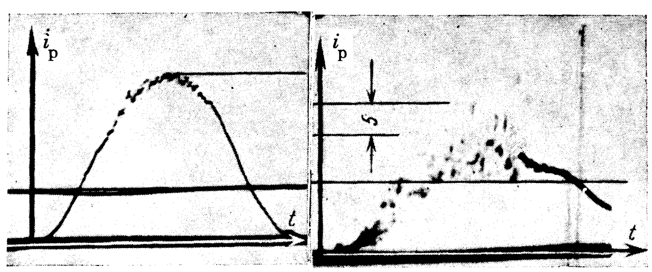


FIG. 6. Arc voltage at $(i_a)_{max}$ = 1700 amp, p = 0.4 μHg.



a *b*

FIG. 7. Probe current at $(i_a)_{max}$ = 1700 amp, p = 1 μHg. *a*--at the axis of the tube, *b*--at the walls.

the average values. The absolute and relative values of these fluctuations increase as the current increases (cf. Figs. 7 and 8). Upon increasing the pressure, on the contrary, these fluctuations decrease (cf. Figs. 6 and 7*b* with Figs. 9*a* and

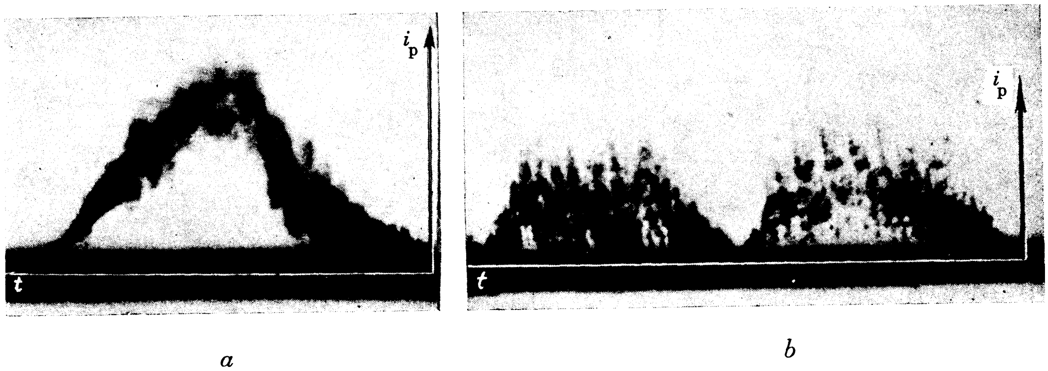


FIG. 8. Probe current at $(i_a)_{max} = 2000$ amp, $p = 0.8\ \mu$Hg. *a*--along the axis, *b*--at the walls.

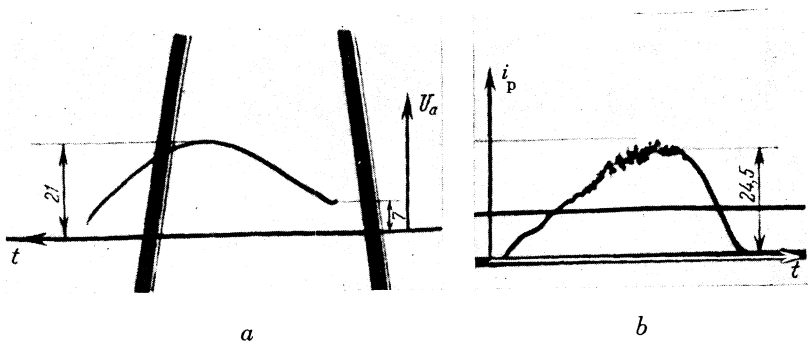


FIG. 9. Arc voltage and probe current at $(i_a)_{max} = 1700$amp, $p = 10\ \mu$Hg. *a*--arc voltage, *b*--probe current at the wall.

9*b*). The fluctuations of the ionic current at the periphery (Figs. 7*b*, 8*b*) and at the walls of the tube are greater than at the axis (Figs. 7*a* and 8*a*).

However, the arc current i_a may not yet experience any noticeable fluctuations (Fig. 10). Considerable fluctuations in i_a begin even at higher currents than the fluctuations in U_a and i_p in the tube with $R = 30$ mm in Hg vapor at 1700-1800 amp($j_a \approx 50$ amp/cm^2) (Fig. 11) when the i_p fluctuations at the edge of the tube approach 100%. Some of our observations of the relative value of the fluctuations in U_a, i_a and i_p at various conditions are compiled in Table II; the accuracy of the values is of the order of 10%. The Table shows clearly that there is an increase in the fluctuations when the current i_a is increased and the pressure p is decreased. A similar dependence of the vibrations on i_a and p was observed also in the other gases. In all cases the value most sensitive to the disturbance of the stability of arc performance was found to be the probe current, then the arc voltage and finally the arc current.

In spite of their chaotic character, these fluctuations occur with a certain average frequency f, which can be evaluated from the oscillograms. The results of such an evaluation are given in Table III. Since the frequencies of the fluctuations i_p and U_a are approximately the same, a common evaluation for both of these is given in the Table.

From the Table it is evident that the average frequency of fluctuations, other conditions being equal, decreases when the radius of the tube is increased, increases with an increase in arc current and decreases with an increase in the molecular weight of the gas.

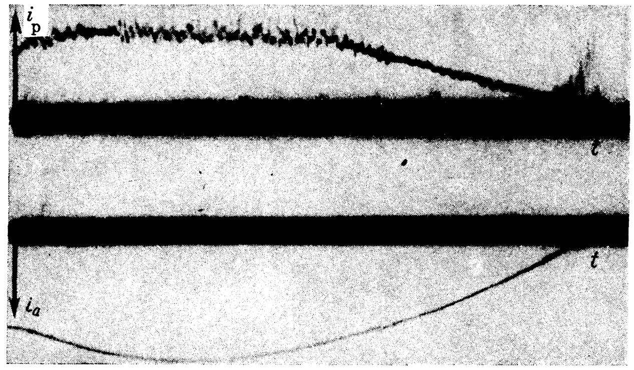


FIG. 10. Probe current i_p and arc current i_a, Ar, $R = 30$ mm, $(i_a)_{max} = 240$amp, $p = 3\,\mu$Hg.

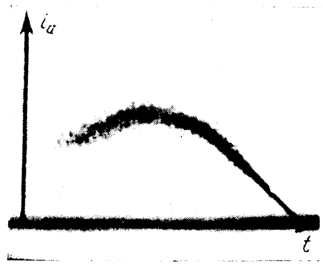


FIG. 11. Oscillogram of the arc current in Hg vapor at $R = 30$ mm, $(i_a)_{max} = 2000$ amp, $p = 0.8\ \mu$Hg.

TABLE II. Fluctuations of i_a, U_a and i_p (in %) (Hg, R = 30-35 mm)

p (μHg)		1	1	1	1	1	0.4	1	10
$(i_a)_{max}$ (amp)		190	440	1000	1700	2000	1700	1700	1700
$\Delta i_a/i_a$		0	0	0	0	25	5	0	0
$\Delta U_a/\overline{U}_a$		0	0	10	25	40	35	25	0
$\frac{\Delta i_p}{\overline{i}_p}$	at the axis	0	0	0	10	50	20—30	10	10
	at the wall	0	0	15	50	90	30—80	50	20

TABLE III. Average frequency $\bar{f}$ of the voltage fluctuations

Gas	R, mm	$(i_a)_{max}$ amp	$\bar{f}$ cycles
Hg	16	1200	$1.2-1.8\times10^5$
	16	1600	$2.6-3.6\times10^5$
	15	1200	$4.5-6.7\times10^5$
Ar	5	1000	$2.0-2.2\times10^5$
Kr	16	1000	$1.0-1.4\times10^5$
	5	1000	$1.6-1.8\times10^5$

c) Observations with two symmetrical probes. The fluctuations of the arc parameters, described above, and primarily of the probe current, can be explained by the fact that at strong currents the arc column is compressed into a narrow cord, and that this cord does not remain stationary, but propagates along the cross section of the tube with the frequency of the fluctuations observed. To verify this hypothesis it would be expedient to register simultaneously the currents on two identical probes, placed in the same cross section of the tube, symmetrical to the axis of the tube (see Fig. 1b). If the arc column actually fills only a portion of the tube cross section and if it propagates with time, then the maxima and the minima of the current on both probes should not appear simultaneously. On the contrary, their synchronized appearance would indicate that there is no arc propagation, but simply fluctuations of the arc current as a whole. In Fig. 12 a sample is shown of the current oscillograms (initial sections) on the two probes registered with a double-ray oscillograph with mechanical resolution. The experimental conditions were: Hg, $R = 30$mm, $p = 1.2\mu$Hg, $(i_a)_{max} = 1000$ amp, $U_a = -55$ V. A comparison of both oscillograms shows that, in addition to the changes occurring simultaneously in both currents, there are also many peaks in each of the currents which do not coincide in time with the peaks of the other current; opposite a peak of one current there are slopes and dips of the other. Moreover, even the numbers of the peaks on both oscillograms do not agree. This and other similar photographs provide proof in favor of the above hypothesis on the irregular propagation of the arc column in the tube.

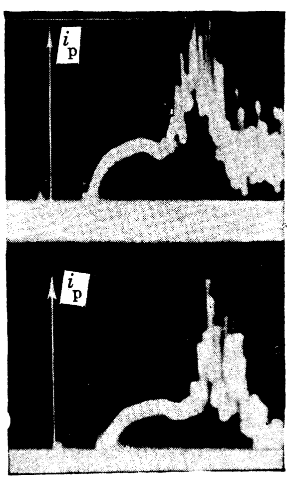
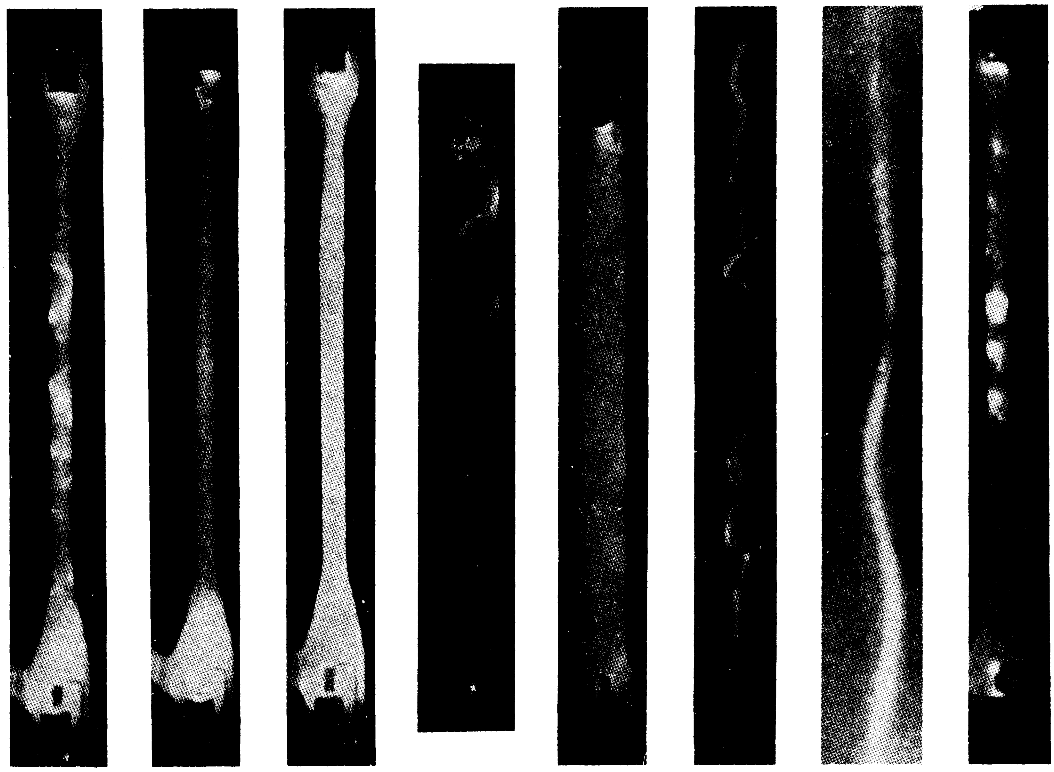


FIG. 12. Probe currents on two identical, symmetrically located probes, registered simultaneously, Hg, $R = 30$ mm, $p = 1.2\mu$Hg, $(i_a)_{max} = 1000$ amp.

d) The shape of the arc column at short pulses. The results of the above-described observations on the behavior of the arc at strong currents, carried out with the aid of probes and of an oscillograph, require direct verification of the fact that at strong currents the arc column is actually compressed into a narrow cord. For visual observation and for photographing the compressed arc column, it is necessary to observe the arc within short time intervals, during which the column is not yet noticeably displaced. From the data on the average frequency of vibrations $\bar{f} \sim 10^5$ cycles it follows that the average period of this assumed displacement $\bar{T} \sim 10\,\mu$sec and therefore the time for observing the arc in a single position should not exceed a few microseconds. By passing strong current pulses of such duration through the tube, one could hope to observe the actual shape of the arc column at high current.

For this purpose condensers, connected to the tubes with short heavy copper conductors, were discharged through our experimental tubes. By discharging capacities of 1-2 μF, charged up to 7-8 kv, through the tubes with diameters of 10 and



13 14 15 16 17 18 19 20

FIG. 13. The arc at a current pulse of 450amp, $\tau = 2\mu$ sec, Hg, $R = 5$ mm, $p = 1\mu$Hg.
FIG. 14. The same as in Fig. 13, $(i_a)_{max} = 220$ amp.
FIG. 15. The same as in Fig. 13, $(i_a)_{max} = 1400$amp, $\tau = 50\mu$sec.
FIG. 16. The same as in Fig. 13, $(i_a)_{max} = 2000$amp, $\tau = 7\mu$sec, Hg, $R = 16$ mm, $p = 0.4\mu$Hg.
FIG. 17. The same as in Fig. 13, $(i_a)_{max} = 2000$ amp, $\tau = 50\mu$sec, Hg, $R = 16$ mm, $p = 0.4\mu$Hg.
FIG. 18. The same as in Fig. 13, $(i_a)_{max} = 1000$amp, $\tau = 1\mu$sec, H_2, $R = 5$ mm, $p = 2\mu$ Hg.
FIG. 19. The same as in Fig. 13, $(i_a)_{max} = 450$amp, $\tau = 1.5\mu$sec, Ar, $R = 16$ mm, $p = 2\mu$Hg.
FIG. 20. The same as in Fig. 13, $(i_a)_{max} = 700$amp, $\tau = 1.5\mu$sec, Hg, $R = 5$ mm, $p = 1.6\mu$Hg.

32 mm filled with vapor of Hg, Ar, Kr and H_2 at pressures of 0.5-10μ, Hg, pulses of current were obtained of 450-2000 amp with a duration of 1-2 μsec (in some cases the pulse duration was artificially delayed up to 50 μ sec). About 100 such photographs were obtained, samples of which are given in Figs. 13-20.

In Fig. 13 a photograph is shown of an arc in Hg vapor at $R = 5$ mm, $p = 1\mu$ Hg and a current pulse $(i_a)_{max} = 450$ amp with a duration of $\tau = 2\mu$ sec. It is clearly evident that, over the major portion of the column, the brightest luminescence emanates from the comparatively narrow region or cord, the width of which is not constant, but does not exceed 2-2.5 mm (tube diameter 10 mm). This cord is bent into a three-dimensional curve approaching a helix with a nonuniform pitch along the length; it adheres closely to the glass walls of the tube.

In Fig. 14 a control photograph is given which was obtained at a current of 220 amp, all other conditions being equal. It is evident that there is no arc compression of any kind: the luminescence fills the entire tube. At a considerably greater arc duration (50 μ sec) (Fig. 15) also, no compression is observed, in spite of the even higher current (1400 amp); evidently in this time the arc has already succeeded in propagating over the entire cross section of the tube. Using a tube with a considerably larger diameter (32 mm), similar phenomena were observed: with a current of 7 μ sec duration arc compression and its curvature in the shape of a helix are clearly visible (Fig. 16), while in the time interval of 50 μsec no compression of any kind can be observed in the photograph (Fig. 17).

This phenomenon is not specific to any particular gas (Hg vapor), it is observed also in hydrogen (Fig. 18), in argon (Fig. 19) and in krypton.

Thus, at high currents the arc column in a rarefied gas is subject to two different deformations -- transverse compression and curvature into the form of a helix, occupying the maximum space accessible to it.

In addition to the transverse compression of the column, at the very low pressures and high currents there can be observed also a longitudinal nonuniformity in the luminescence, which is also periodic in character. As an example, we can cite the photograph in Hg at $R = 5$ mm, $p = 1\,\mu$Hg, $(i_a)_{max} = 700$ amp and $\tau = 1.6\,\mu$sec (Fig. 20). The same phenomenon occurs in the other gases.

e) Propagation of the arc during prolonged time intervals.

From the earlier results one can conclude that the arc column is also compressed during a prolonged passage of current, but the compression is not noticeable because of the rapid propagation of the arc. The latter also requires substantiation by direct experiments.

Such experiments were carried out according to the diagram of Fig. 3; a "transverse section" (thin layer) was isolated from the arc column, the image of which in the form of a narrow band was photographed on a moving film. If the arc is actually compressed and is propagating, then the image of the arc cross section should be compressed into a single spot; this spot should propagate with time in a zigzag fashion along the photograph.

In Fig. 21, a photograph is shown of the arc element in a tube with a diameter of 32 mm in Hg vapor at $p = 10\,\mu$Hg and a pulse current of ~ 1200amp at $\tau = 400\,\mu$ sec obtained on a moving film. On the left, a photo is shown of the same band, but on a stationary film; below the oscillogram of the arc current is shown. The photo-resolution shows that the luminescence of the arc element at maximum currents is actually

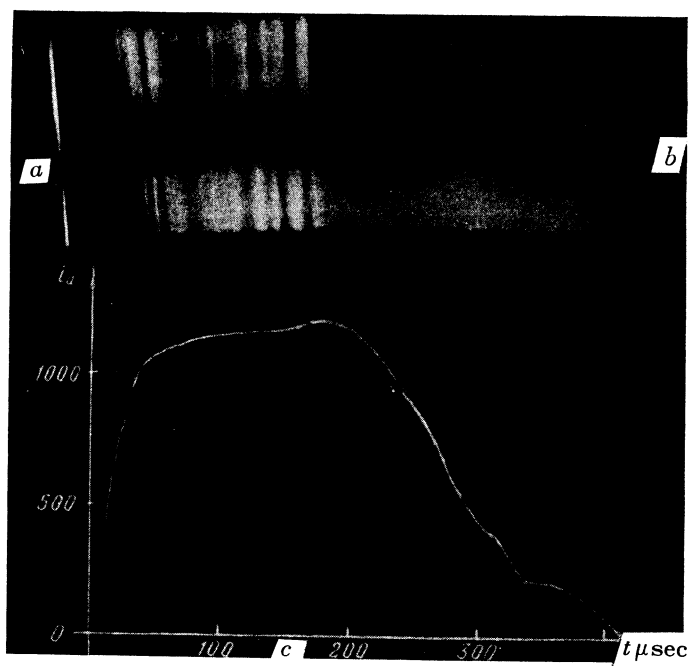


FIG. 21. a--photograph of the narrow band of the arc on a stationary film, b--the same on a moving film, c--oscillogram of the current.

concentrated into one spot and that this maximum of the luminescence is moving back and forth along the entire tube diameter*. The period of thispropagationis on the average 13-15μ sec, which corresponds to an average frequency of $\sim 0.7\text{-}0.8 \times 10^5$ cycles. When the current drops, the arc compression and propagation break off abruptly.

The visible propagation of the arc section in a single plane in the photograph does not signify that the propagation itself necessarily takes place in a single plane. The observed horizontal propagation may be a projection of the three-dimensional propagation, for example, around the periphery adjoining the walls of the tube.

4. DISCUSSION OF RESULTS

The combination of all the results obtained by probe measurements, by oscillographic measurements and by photographic resolution of a continuous luminous arc, as well as by observations with short current pulses, leaves no doubt as to the existence of the phenomenon itself. One can consider as experimentally proved the fact that the arc in highly rarefied gases ($p \sim 10^{-3}$ mm Hg) at considerable currents($i_a \sim 10^2 - 10^3$ amp): 1) is compressed into a narrow cord in a transverse direction, occupying a small portion of the volume of the tube, 2) it is curved into a three-dimensional helix, adhering to the inner surface of the tube walls in the majority of cases, 3) at a duration of discharge $\geq 10^{-5}$ sec, it is rapidly and irregularly propagated along the cross section of the tube.

What is the possible explanation of these phenomena?

The compression of the arc channel, other conditions being equal, may have various explanations.

a) At high gas pressures the arc column contracts towards the axis of the tube owing to the heating of the gas, which is maximum at the axis. However, in our case this interpretation does not apply. First, in our experiments the gas pressure does not exceed 10 μHg in Ar and Hg and a few microns in the other gases; therefore, the length of the free path of molecules in all cases was equal to or greater than the radius of the tube R. Under these conditions no considerable difference in the temperatures of the gas at the axis and at the walls could be established. Second,.in the experiments with current pulses of a few microseconds duration the temperature of the gas could not increase by more than a hundred degrees or so*, as can be shown by a simple calculation. Thirdly (and this is the most important), at such low gas pressures (10^{-3} mm Hg) the rarefaction of the gas, inevitably originating at the place of the greatest heating, in this case only decreases the intensity of ionization by comparison with the neighboring, more dense reion of the gas, since the voltage of the longitudinal field E is everywhere equal and, therefore, here it will decrease and not increase the current density. Hence, the explanation of the contraction of the column, relating to the high pressure arc, does not apply here.

b) The idea about the gas focusing electron ray, through which the low pressure arc column is developed, put forward in Ref. 12, also does not apply here, since it cannot explain the prolonged stay of the column in a compressed state, when the current has already attained a maxumum value; in addition, it does not explain the absence of compression at a lower current (200 amp) and the appearance of compression at the higher current (400 amp) (see Figs. 13 and 14).

c) On the other hand, the concept of the electrodynamic action of the self-magnetic field of the arc explains all of the main features of the observed phenomena. As was shown in a number of theoretical papers[2-5], the self-magnetic field sets up in the arc a radial pressure directed towards the axis and compresses the arc column. Its action should become noticeable in the time in which the motion of electrons becomes established, that is, $10^{-7} - 10^{-8}$ sec, and it should continue as

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* Longitudinal bands of lower brightness are not associated with the processes in the arc, since they are noticeable also on the stationary photograph, but are, apparently, dependent on defects in the glass of the tube and in the slits.

* We will assume that the gas is heated as a result of the elastic collisions of electrons. The kinetic energy, transferred at each such collision, on the average is equal to $2(m_e/m_g)3/2kT_e$, the number of such collisions in the volume dV in time τ is $(\bar{c}_e/\lambda_e)n_e \tau dV$, and the energy transferred is $3(m_e/m_g)kT_e(\bar{c}_e/\lambda_e)n_e\tau dV$. If we neglect the heat exchange in the gas, then this value is equal to the increase in the internal energy of the gas, that is, $3/2n_g dVk\Delta T_g$. Assuming in $n_e = n_g$ (100% ionization), we find $\Delta T_g = 2(m_e/m_g)(\bar{c}_e/\lambda_e)\tau T_e$. If we take $m_e/m_g = 2.7 \times 10^{-6}$ (Hg), $T_e = 2.5 \times 10^5$ °C (according to some evaluations), $\bar{c}_e = 10^8$ cm/sec, $\lambda_e \sim 10$ cm, then even at $\tau = 10\mu$sec $\Delta T_g = 130°$ C. At lower τ, ΔT_g will be less.

[12] G.V. Spivak and E.L. Stoliarova, J. Tech. Phys. (U.S.S.R.) 20, 501 (1950).

long as the current is sufficiently high. This action should be the stronger, the higher the degree of the gas rarefaction and the higher the current; the one and the other actually take place. By a very rough approximation, currents of $10^2 - 10^3$ amp, which were used in these experiments, are sufficiently high for their magnetic field to change essentially the distribution of the carrier concentrations along the cross section of the tube. In fact, the radial component of the electric field in the column is on the average

$$\overline{E}_r \sim -\frac{d(\ln n)}{dr}\frac{D_e}{b_e} \sim \frac{kT_e}{e_0}\frac{\Delta n_e}{n_e}\frac{1}{R}$$

$$\sim 1\ \mathrm{V/cm} \sim 3\times10^{-3}\ \mathrm{CGS}$$

The force of the magnetic field current is

$$vB/c_0 \sim 2i_a \cdot 10^8 / R \cdot 3\times10^{10} \sim 10^{-3} i_a.$$

Hence, even when $i \sim 3$ abamp = 30 amp, it is comparable with the radial electric field; but when $i_a \sim 10^2 - 10^3$ amp, it exceeds the latter by many times.

Hypotheses a) and b) also do not explain the curvature of the column into a helix adhering to the walls of the tube. One cannot admit that the most intense heating of the gas by the current should originate along such a helix, or that along it should occur the initial breakdown of the gas. On the contrary, the electrodynamic theory explains easily also this aspect of the phenomenon as a manifestation of the fairly common property of current -- the instability of the linear form of the current with respect to the self-magnetic field.

Each deviation of the current from the strictly linear form gives rise to an electrodynamic force, increasing this deviation. According to a well known principle of electrodynamics, this change will proceed in the direction of increasing magnetic energy of the current [13], from here -- the tendency of the transition of the linear current into the helix form. For the manifestation of this it is necessary that the electrodynamic forces should exceed the elastic (in solid conductors) or the dissipative forces, counteracting the change in the form of the current. In the high pressure arc this phenomenon is well known[14]. Our experiments showed the presence of such a phenomenon also in the low pressure arc at high currents. Their results agree with the conclusions of the theoretical analysis on the stability of the arc plasma with respect to transverse perturbations[4]. They substantiate also the general conclusion[15, para 74] that at a large current the magnetic field is the main reservoir of the current energy in the gas and, therefore, the main factor determining its dynamics, by comparison with which the difference in the gas pressure begins to play a lesser role.

Regarding the rapid propagation of the arc along the cross section of the tube, the cause of this may be different -- not electrodynamic but gasodynamic. A certain small rarefaction of the gas as a result of its heating in the arc channel (above it was evaluated $< 100°$) leads to the fact that the ionization of the gas by electron collisions becomes more intense in the adjacent non-rarefied sections of the volume. It is here that the arc displaces from its previous heated channel.

According to this concept, the propagation of the arc should occur with a velocity of the order of the velocity of the motion of the gas molecules, that is, $10^4 - 10^5$ cm/sec. In that case, the average frequency of these displacements should be of the order of $c_g/R \sim 10^4 - 10^5$ cycles, and this was actually observed.

Certain details of the observed phenomena remain outside this picture; for example, the longitudinal non-uniformity of the luminescence, observed at the very low pressures and at high i_a. At present there is not enough data to formulate an opinion about these. One may only assume that here the forces of the electrostatic interaction between the charges in the plasma come into play, to which much attention has recently been paid[16].

5. CONCLUSIONS

1. Studies with the aid of a movable probe showed that the half-width of the arc column in a rarefied gas (Hg vapor) in a tube of radius R = 30-35 mm at $p \sim 1\,\mu$ Hg decreases by 30%,

[13] J.C. Maxwell, *Selected Works on the Theory of the Magnetic Field,* Moscow, 1952 (Russian Translation); V. F. Mitkevich, *Physical Basis of Electrotechniques*, Leningrad, 1933.

[14] L.A. Sirotinskii (editor), *High Voltage Techniques*, Part 1, State Energetics Press, Moscow, 1951, para. 11.

[15] V.L. Granovskii, *Electric Current in a Gas* **1**, Moscow, 1952.

[16] A.A. Vlasov, J. Exptl. Theoret. Phys. (U.S.S.R.) **8**, 291 (1938).

when the current increases up to ~ 170 amp. It was not possible by this method to observe any further compression of the arc upon increasing the current up to 2000 amp, owing to the origination of strong fluctuations in the performance of the arc.

2. Increasing the current above 10^2 in rarefied gases (Hg, Ar, Kr, H_2) gives rise to strong fluctuations in the parameters of the arc: first, in the probe current, then in the arc voltage and finally, in the arc current. The amplitude of these vibrations increases with an increase in i_a and a decrease in p. The frequency of these vibrations is of the order of 10^5 cycles; it increases with an increase in i_a and a decrease in R and in the molecular weight of the gas.

3. The oscillographic measurements of the currents on two identical, symmetrically located probes show that the above fluctuations may be explained as a result of the compression of the arc column into a narrow cord and of its irregular propagation along the cross section of the tube.

4. The compressed arc column at low pressures (a few microns Hg) may be observed visually and photographically in all the above-mentioned gases at short current pulses, in the time interval of which the arc had not succeeded in displacing ($\tau = 10^{-6}$ sec). The arc column was found to be compressed into a narrow cord, curved approximately into a helix, adhering to the walls of the tube.

5. For prolonged passage of current, the arc column, as is shown by the photo-resolution of the transverse cross section of the tube, remains compressed, but it propagates rapidly along the cross section of the tube.

6. The compression of the arc column into a narrow cord and its curvature into a helix can be explained by the electrodynamic action of the self-magnetic field of the arc.

7. Its propagation can be explained by the gasodynamic action of the arc channel -- rarefaction of the gas in the arc channel.

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