SOVIET PHYSICS

JETP

A translation of Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki.

Vol. 13, No. 2, pp 263-501 (Russ. orig. Vol. 40, No. 2, pp 385-720, Feb., 1961) August, 1961

CHANNEL EXPANSION IN SMALL INTENSE SPARKS

B. A. DEMIDOV, Yu. F. SKACHKOV, and S. D. FANCHENKO

Submitted to JETP editor June 3, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **40**, 385-390 (February, 1961)

An electron-optical chronograph has been used to study the initial stages of channel expansion in sparks in oxygen and nitrogen (at pressures up to 10 atm), in deuterium (13 atm) and in hydrogen (up to 20 atm) produced by discharging low-inductance capacities of 30 and 6300 $\mu\mu$f. The maximum rate of rise of the current is of the order of 3×10^{12} amp/sec, the calculated peak current approximately 10^3 amp, and the calculated current density $10^8 - 10^9$ amp/cm^2. The initial expansion of the spark channel is due to a cylindrical shock wave which propagates at a velocity up to 6×10^6 cm/sec in nitrogen, up to 8×10^6 cm/sec in hydrogen and up to 7×10^6 cm/sec in deuterium (in the last case the temperature at the shock wave front is approximately 8 ev). The calculated temperature in the spark channel in hydrogen is approximately 22 ev.

1. INTRODUCTION

ACCORDING to contemporary ideas, the development of a spark discharge in a high-density gas takes place in two stages. The first state is terminated when the discharge gap is bridged by the electron-photon streamers which are formed in this gap. The second stage starts with the flow of a high current through the conducting bridge which has been formed; this current causes intense Joule heating of the gas in this bridge, transforming it into a brightly emitting, thread-like channel. It has been known for a long time that rapid channel expansion starts as soon as the channel is formed and that the channel boundaries remain clearly defined throughout the expansion process. The expansion of spark channels has been studied by a number of authors,[1-10] who have generally used high-speed cameras with rotating photographic films or mirrors. The cameras used in these investigations provided continuous recording with a time resolution up to 3×10^{-8} sec.

In the work cited above, particularly that of S. L. Mandel'shtam and his colleagues,[1,3,5-7] it has been shown that the initial expansion of the spark channel, which is characterized by the highest velocity, is due to the propagation of a shock wave in the gas. This shock wave causes preliminary heating and ionization of the gas which is drawn into the channel. It has been found that the initial velocity of propagation of the channel is very sensitive to the inductance in the discharge circuit, increasing as the initial current derivative $(dI/dt)_0$ increases. For this reason we have undertaken an investigation of the initial stages of channel expansion in a discharge circuit with a higher value of dI/dt than has been available to the workers in the work indicated above.

2. DESCRIPTION OF THE APPARATUS

Discharge Circuits

a) Disc capacitor. Two discs, 7 cm in diameter, separated by a distance of 1 mm in the gas being studied, form a 30-$\mu\mu$f capacitor. The spark always occurs at the center of the discs, because of the presence of a point there (Fig. 1a). The period of the natural oscillations of this discharge circuit is determined by observation of periodic variations

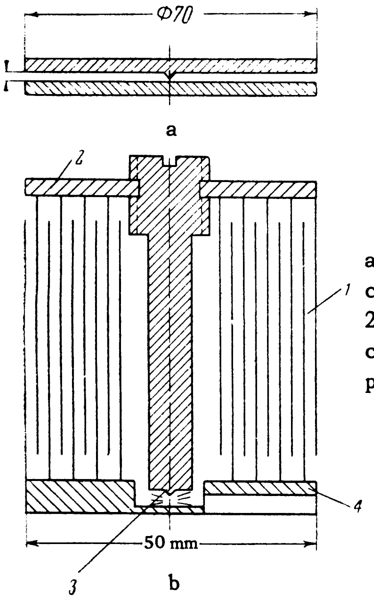

FIG. 1. Discharge circuits. a) disc capacitor, b) coaxial capacitor; 1) foil electrodes, 2) upper plate with coaxial current-conducting rod, 3) point, 4) lower plate.

in the emission intensity of the spark and is found to be 2×10^{-9} sec. An additional check is provided by measurement of the wavelength of the radio wave produced by the discharge; this check shows qualitative agreement with the results of the optical measurements of the oscillation period. The total inductance of the circuit, as computed from the period of the natural oscillations, is 3 cm.

b) Coaxial capacitor. In Fig. 1b we show a low-inductance coaxial capacitor of the type suggested by Fischer[11] which has been developed for the present work. The spark occurs between point 3 and the lower plate 4. The capacitance is 6300 $\mu\mu$f and the total inductance of the discharge circuit is 7 cm.

Method of Observation

In addition to using a camera with a rotating mirror, we have employed an electron-optical chronograph[12] which, in principle, permits a time resolution of approximately 10^{-14} sec. In the present case the time resolution was approximately 10^{-10} sec and was completely adequate for the purposes of this investigation.

The image of the spark 1 (cf. Fig. 2) is projected by the objective lens 2 on the input photocathode 4 of a multistage electron optical image converter (EOC). A narrow slit 3, is located in front of the photocathode; this slit isolates a short section of the channel image. The electron image of this portion of the channel is swept in time by the deflection plates 5, 6, to which is applied an alternating voltage at frequencies of 5, 11, and 21 Mc/sec (in certain experiments 1 Mc/sec). The sweep is along the longitudinal dimension of the channel. The time-swept image of the expanding spark channel passes through several stages of electron-optical amplification;[13,14] the intensified image on the output luminescence screen[7] can then be photographed with a conventional camera 8. In order to obtain good photographs we have used a pulsed spark supply and the EOC. In Fig. 2 we also show the voltage pulse which produces the image of the spark on the output screen at the appropriate time.

3. RESULTS

Examples of photographs obtained with the discharge circuit shown in Fig. 1a are given in Figs. 3 and 4. In most of the photographs obtained there is a periodic variation in the emission intensity from the spark channel caused by the natural oscillations of the discharge circuit (period approximately 2×10^{-9} sec). In hydrogen (Fig. 3) these brightness variations are observed over the entire range of initial pressures which has been studied, 2 — 20 atm. In nitrogen, the periodic variations in brightness are clearly visible at pressures above 6 atm (Fig. 4); at 6 atm they become weak, and at 4 atm or below cannot be observed at all.

Many cases in which the channel splits into two parts have been observed in nitrogen. In agreement with observations which have been published earlier by other authors, we have observed a noticeable repulsion between the two channels which result from

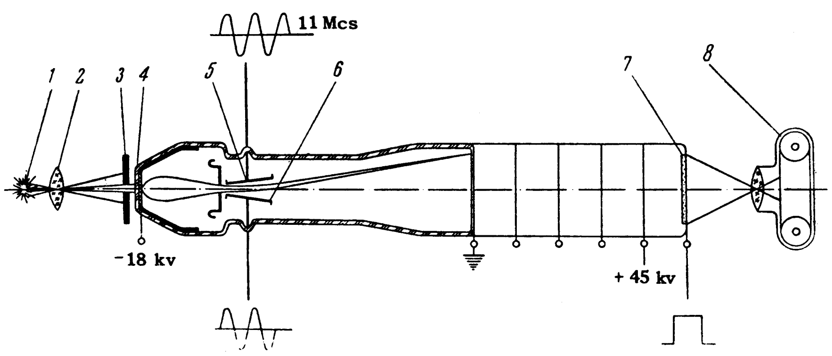

FIG. 2. Diagram of the apparatus.

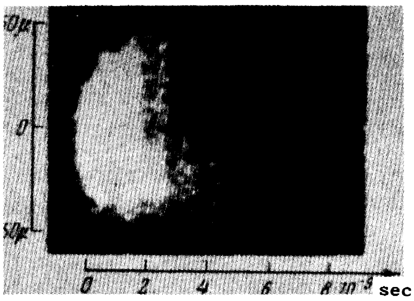

FIG. 3. Expansion of a spark channel in hydrogen at a pressure of 12 atm. Time is plotted along the abscissa axis while the spark diameter is plotted as the ordinate.

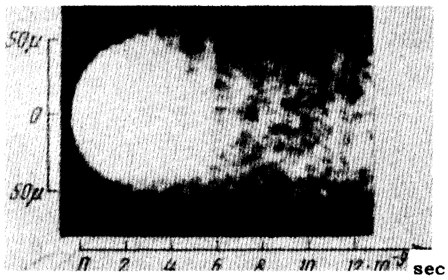

FIG. 4. Expansion of a spark channel in nitrogen at a pressure of 8 atm.

splitting. Many cases have also been observed in which channel expansion is not completely symmetric.

The general pattern of channel expansion and the order of magnitude of the expansion velocity in oxygen are the same as in nitrogen.

The highest expansion rate is observed in the first quarter of the natural oscillation period of the discharge circuit (τ). This rate is estimated by dividing the channel radius at approximately $\tau/4$ by the elapsed time from the beginning of the expansion process. It should be noted that with identical initial discharge conditions (gas pressure and gap length) the initial expansion rates vary by a factor of several times in individual cases. Special photographs of the entire channel, which were taken with slit 3 removed and with no sweep show that the channel is usually twisted and kinked and that the emission intensity is not uniform over the channel. The spread in the observed expansion rate is apparently due to the fact that images of widely different portions of the channel reach the slit 3. In considering this spread we may note that in our measurements physical significance is to be given to only the highest observed value of the initial expansion rate, which is determined with an accuracy of 10%.

In nitrogen (sweep frequency 11 Mc/sec) the observed expansion velocity is as high as 6×10^6 cm/sec. In hydrogen a faster sweep is used (21 Mc/sec); hence, in determining the rate of expansion we use a value of the channel radius corresponding to an earlier time, specifically, $\tau/8$. In this case, the highest measured expansion velocity in hydrogen is found to be 8×10^6 cm/sec. In deuterium (initial pressure 13 atm) the highest measured velocity is 7×10^6 cm/sec.

Comparative data obtained in investigations of spark channel expansion by different authors.

Literature reference	Electrical parameters of the discharge circuit				Spark parameters			
	Capacitance C, μF	Current, amp	$(dI/dt)_0$, amp/sec	Period of the natural oscillations of the discharge circuit, μsec	Gas	Pressure atm	Maximum current density, amp/cm²	Initial rate of expansion of the channel, 10^5 cm/sec
[2]	—	10^4–10^5	10^{10}*	Aperiodic pulse, t = 10–1000	Air	1	$2.7 \cdot 10^4$	2
[4]	—	500	10^9–10^{10}*	Aperiodic pulse, t_{rise} = 0.25, t_{fall} = 10–28	Air Nitrogen Oxygen Hydrogen	1 1 1 1	$3 \cdot 10^4$ $3 \cdot 10^4$ $3 \cdot 10^4$ $7 \cdot 10^4$	0.93 2*
[6]	0.0035–0.25	10^4–10^5	10^8–10^{10}*	0.5÷30*	Air Hydrogen Argon	3 1 1	$6 \cdot 10^6$	3 4 3
[8]	—	200	10^9–10^{10}*	Rectangular pulse, 4–10	Hydrogen	1	10^5–10^6*	10*
[9]	57	$2.65 \cdot 10^5$	$5 \cdot 10^{10}$*	30	Air Argon Hydrogen	1	$7 \cdot 10^4$ $9 \cdot 10^4$ $2 \cdot 10^5$	3 9 2
[10]	132	$2 \cdot 10^6$	$1 \cdot 10^{12}$	17*	Air	1	$9 \cdot 10^6$	20
Present work	0.00003	10^3	$3 \cdot 10^{12}$	0.002	Oxygen Nitrogen Hydrogen Deuterium	10 20 13	10^8–10^9	60 60 80 70
	0.0063	10^4	$2 \cdot 10^{12}$	0.04	Nitrogen Hydrogen	10 18	10^7	25 60

*This quantity is not given in the cited work; it is computed on the basis of other data reported in the paper.

The discharge circuit shown in Fig. 1b has been used to investigate the expansion of a spark channel in nitrogen and hydrogen at pressures from 1 to 18 atm. The maximum initial expansion velocity in nitrogen was found to be 2.5×10^6 cm/sec and the maximum in hydrogen, 6×10^6 cm/sec.

4. DISCUSSION OF THE RESULTS

Comparative data for the parameters of discharge circuits used by various authors and values of the observed expansion rates are given in the table. The data given for the present discharge circuits are computed from the known capacity, the period of the natural oscillations, and the breakdown voltage; ohmic resistance is neglected.

The table shows that in spite of its low capacity and simplicity of construction, the first discharge circuit used in our work provides the highest initial current derivative and the highest initial channel expansion rate. Comparison of the initial channel expansion rates for our first and second discharge circuits, and of our data with the data of other authors, emphasizes the dependence of the initial expansion rate on $(dI/dt)_0$.

In the present experiments the shock waves have not been recorded by the Teller method. Only the brightly illuminated region of the discharge was photographed. For this reason it was not possible to observe experimentally the time at which the shock wave breaks away from the channel. However, there is little doubt that the initial stage of expansion, which is the only one for which we estimate velocity, precedes this breaking away. If we assume that in this stage the boundary of the luminous region is a shock front and compute the temperature from the measured expansion rate, then, as is shown below, the temperature in the shock front is found to be sufficient for total ionization of the gas drawn into the discharge channel. Thus, in the present case we are not dealing with the mechanism considered by Mandel'shtam et al.[3,6] in which the shock wave breaks away from the channel because of the inadequate conductivity in its front.

On the other hand, simple estimates show that in our experiments the current and the magnetic field of the plasma itself are inadequate to constrict the channel by the pinch mechanism. This effect as has been observed in high-current discharges by Komel'kov and Parfenov.[10]

For total ionization of the gas in the shock front the temperature in the front in hydrogen is given by the following expression:[15]

$$T_f = 3.95\,(D/9\cdot 10^6)^2\left[1-(9\cdot 10^6/D)^2 + \sqrt{1+\tfrac{2}{3}(9\cdot 10^6/D)^2}\,\right], \tag{1}$$

where T_f is the temperature in the shock front in ev and D is the velocity of the shock wave in cm/sec.

According to (1) a wave velocity $D = 8 \times 10^6$ cm/sec corresponds to $T_f = 3.5$ ev. In deuterium the velocity of the shock wave, 7×10^6 cm/sec, corresponds to a temperature $T_f = 8$ ev.

The gas ionization for the obtained values of temperature and high pressure at the front of the shock wave can be estimated by the Saha equation; it is found that essentially all of the gas is ionized.*

It is also interesting to estimate the temperatures and densities of sparks in hydrogen on the basis of a hydrodynamic analysis of the spark channel; this theory has been given by Drabkina[5] and developed by Braginskii.[17] Applying Eq. (3.13) of reference 17, we obtain a channel temperature $T_c = 22$ ev and a channel density $n_c = 3 \times 10^{20}$ cm^{-3}. It should be noted that the formulas in reference 17 are known to apply for sparks with low initial pressures; strictly speaking, this applicability has not been demonstrated in the present case. Nonetheless, it is interesting to compare the temperature which has been obtained with the data reported by Fischer,[11] who has estimated the temperature of a spark channel in helium at a pressure of 35 atm from the spectral distribution of the radiation and finds a value $T_c \sim 25$ ev.

In conclusion the authors wish to thank E. K. Zavoĭskii for valuable comments and continued interest in this work and S. I. Braginskii and S. L. Mandel'shtam for many valuable comments and discussions.

[1] I. S. Abramson and I. S. Marshak, JETP 12, 632 (1942).

[2] J. W. Flowers, Phys. Rev. **64**, 225 (1943).

[3] Abramson, Gegechkori, Drabkina, and Mandel'shtam, JETP **17**, 862 (1947).

[4] J. B. Higham and J. M. Meek, Proc. Phys. Soc. (London) **B63**, 649 (1950).

*Because of possible relaxation processes the use of the Saha equation is not completely valid in this case. However, according to an estimate made by Mandel'shtam and Sukhodrev,[16] at an electron concentration of approximately 10^{21}cm^{-3} the time needed for establishing a steady state for ionization in the spark channel is $\tau \approx 10^{-11}$ sec, which is an order of magnitude higher than the resolution time in the present experiment.

[5] S. I. Drabkina, JETP **21**, 473 (1951).
[6] I. M. Gegechkori, JETP **21**, 493 (1951).
[7] K. S. Vul'fson and I. Sh. Libin, JETP **21**, 510 (1951).
[8] R. D. Craig and J. D. Craggs, Proc. Phys. Soc. (London), **B66**, 500 (1953).
[9] J. E. Allen and J. D. Craggs, Brit. J. Appl. Phys. **5**, 446 (1954).
[10] V. S. Komel'kov and D. S. Parfenov, Doklady Akad. Nauk SSSR **111**, 1215 (1956), Soviet Phys.-Doklady **1**, 769 (1957).
[11] H. Fischer, J. Opt. Soc. Am. **47**, 981 (1957).
[12] E. K. Zavoĭskii and S. D. Fanchenko, Doklady Akad. Nauk SSSR **100**, 661 (1955); **108**, 218 (1956) [the second article is translated in Soviet Phys.-Doklady **1**, 285 (1957)].
[13] Zavoĭskii, Butslov, and Smolkin, Doklady Akad. Nauk SSSR **111**, 996 (1956), Soviet Phys.-Doklady **1**, 743 (1957).
[14] Butslov, Zavoĭskii, Plakhov, and Smolkin, Атомная энергия (Atomic Energy) **1**, 34 (1956).
[15] A. C. Kolb, Phys. Rev. **107**, 345 (1956).
[16] S. L. Mandel'shtam and H. S. Sukhodrev, JETP **24**, 701 (1953).
[17] S. I. Braginskii, JETP **34**, 1548 (1958), Soviet Phys. JETP **7**, 1068 (1958).

Translated by H. Lashinsky
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