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New Instruments and Measurement Methods

HIGH-INTENSITY PULSED LIGHT SOURCES

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INTRODUCTION

In many problems involving high-speed photography, stroboscopic observation of periodic processes, optical location, and investigations of the kinetics of photochemical reactions, photoconductivity, luminescence, etc., it becomes necessary to produce, for a brief time interval, a high level of illumination on the observed, investigated, or photographed object. If optical systems are used to concentrate light beams, high-intensity light sources (in which the light is produced by a body of great brightness) become particularly important.

The brightness of a source of illumination is determined primarily by the temperature of the glowing substance. The maximum temperatures that can be obtained in solids are ~ 4000°K, those in liquids are ~ 6000°K. Only gases or vapors can exist at higher temperatures. As the temperatures increase, the degree of ionization of a gas increases and the gas turns into plasma. The plasma temperature may reach very high values, reaching 10^7 to 10^9 °K in thermonuclear reactions.

It must be borne in mind that when light sources with glowing plasma are considered, they are volume sources and that the power radiated per unit surface of the glowing body into a unit solid angle per unit spectral interval, called the spectral energy density b_λ, is determined by the following expression

$$b_\lambda' = b_\lambda^* (1 - e^{-k_\lambda l}),$$

where b_λ^* is the black body spectral energy density at a temperature T, equal to the temperature of the light source; k_λ is the absorption coefficient of the plasma for radiation of wavelength λ and l is the thickness of the glowing body (the plasma temperature is assumed constant over the entire glowing volume).

The foregoing expression shows that the brightness of a plasma light source depends not only on the temperature but also on the thickness of the radiating layer and on the absorption coefficient of the plasma. The maximum brightness that can be obtained at a given temperature is determined by the black-body radiation laws. An example of a high temperature light source that has a relatively low intensity of continuous radiation is the low-pressure, high-power pulsed electric gas discharge, used to effect controllable thermonuclear reactions. A compression of the discharge resulting from the pinch effect produces in the plasma a temperature of several millions of degrees. However, owing to the high transparency of the plasma[1] (the mean free path of the photons in the discharge is usually many times greater than the dimensions of the discharge chamber) this discharge channel is of low brightness.

In this survey we examine methods of producing high-brightness pulsed light sources, and also methods for measuring their emission characteristics.

I. SPARK DISCHARGE IN GASES

One of the most widely used pulsed light sources, in which the glowing body has a high instantaneous brightness, is produced by a spark discharge in high-pressure gases.

The spark-discharge radiation is caused by the retardation of the electrons in the field of the positive ions (free-free transitions), electron-ion recombination (free-bound transitions), and radiation of greatly broadened lines (bound-bound transitions).[2] For hydrogen and hydrogen-like atoms, Unsold[3] obtained an expression for the spectral distribution of the plasma radiation. However, radiation from the powerful spark discharge that is usually used as a source of light is closer in its spectral characteristics to black-body radiation.[4]

As early as in 1852, Talbert[5] has used the flash produced when a capacitor charged to high voltage is discharged through an air gap to photograph fast objects. Recently pulsed spark lamps appeared, in which the discharge is produced in an atmosphere of heavy inert gases (argon, crypton, or xenon) at gas pressures of several atmospheres. Such lamps have a greater light yield than an ordinary spark discharge in air, but also a considerable longer glow time.

During the last two decades low-pressure pulsed lamps have become widely popular among photographers. These usually are filled with xenon and produce approximately 30 to 40 lumens per watt. However, we shall not consider these lamps, the brightness of which is relatively small.

In this section we shall consider the conditions under which maximum brightness is obtained with a pulsed electric discharge in gases at high pressure, in the case when the glowing body is a current-carrying channel that makes no contact with the walls of the chamber.

I. 1. Methods of Producing High-Intensity Spark Discharges

To produce high brightness in the spark-discharge channel it is necessary above all to insure the maximum possible speed of power intake by the channel. This is obtained by discharging at a sufficiently high voltage, low inductance in the discharge circuit, and high gas pressure.

An idea of the influence of individual parameters of the discharge circuit on the speed of power intake by the discharge gap can be gained from considering the current variation in a damped oscillating discharge. At the beginning of the discharge (during the first half cycle of current), the current i is given with sufficient accuracy by the following expression

$$i \cong U_0 \sqrt{\frac{C}{L}} \sin \omega t,$$

where U_0 is the initial capacitor voltage, C the capacitance and L the inductance of the discharge circuit, $\omega \cong 1/\sqrt{LC}$ the natural frequency of the discharge circuit, and t the time.

The rate of current build up in the discharge, di/dt, determines in first approximation the rate of power intake by the spark gap. Differentiation of the expression for the current shows that at the initial instant of time di/dt depends only on the voltage and inductance of the discharge circuit

$$\left(\frac{di}{dt}\right)_{t=0} = \frac{U_0}{L}.$$

The maximum value of the current in a low-damping circuit is given by

$$i_{\max} = U_0 \sqrt{\frac{C}{L}}.$$

The rate of broadening of the channel also affects the instantaneous energy density in the channel. Using discharges in air at pressures of 200 mm Hg and 3 atmos as examples, Gegechkori[6] has shown that the radius of the channel increases more slowly at increased pressure. It was also established[7] that, other conditions being equal, the speed of broadening of the channel varies in different inert gases and diminishes with increasing atomic weight of the gas. The channel diameter d, measured 5 to 8 μsec after the start of the discharge, when its subsequent change becomes insignificant, depends on the capacitor voltage U_0, the molecular weight of the gas M, and its pressure p in the following manner:

$$d = B \sqrt{\frac{U_0}{pM}},$$

where B = 28 for a circuit with C = 1.09 μf and L = 0.6 microhenry (the voltage U_0 is in kilovolts and p is in atmospheres).

Based on the above considerations, the discharge channel, other conditions being equal, is expected to have a higher instantaneous brightness in heavy inert gases than in the lighter ones. Actually, the reverse is true, owing apparently to the fact that the plasma temperature is dependent to a great degree on the specific heat, the heat conduction, and the electric conductivity of the gas, which at high temperatures depend in turn on the ionization potential rather than on the difference in the diameters of the current-conducting channels, a difference caused by the unequal rate of their broadening.

If pulsed lamps are made in sealed glass or quartz bulbs, the pressure seldom exceeds 5 to 8 atmos, in order to reduce the danger of the bulb bursting. To produce a discharge at higher pressures it is possible to use dismountable pulsed lamps.[4,8,9,11,14] Vanyukov et al.[8] describe the construction of a lamp that operates at 10 atmos. Data are also published on light from a spark discharge in hydrogen at pressures up to 95 atmos.[9]

To construct high intensity spark light sources it becomes necessary to develop special low-inductance, high-voltage capacitors and to devise the most suitable methods for connecting these capacitors to the discharge gap. In such light sources the capacitor and the pulsed lamp proper usually comprise an integral unit. To reduce the inductance of the discharge circuit it is necessary to aim for such an arrangement of the circuit elements, at which the magnetic field formed by the current is contained in the smallest possible volume.

Data on low-inductance capacitors and discharge circuits are reported in references 8 to 16. By way of an example, we cite certain characteristics of low-inductance capacitors used in high-speed photography. Fayole and Naslin[13] report on a circuit with C = 0.004 μf and an L = 0.006

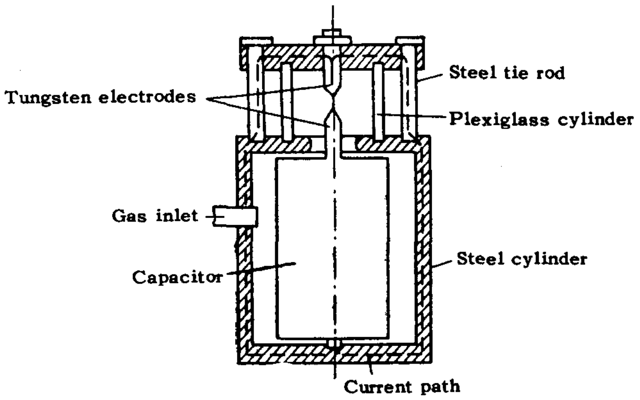

FIG. 1. Diagram of a dismountable pulsed lamp with capacitor placed inside the lamp housing (C = 0.1 μf, U_0 = 12 kv, L = 0.03 microhenry).

microhenry, obtained with specially designed ceramic capacitors. A feature of another type of low-inductance 0.01-μf capacitor is that it produces a 2-joule aperiodic discharge which is completed within practically 10^{-7} seconds.[13]

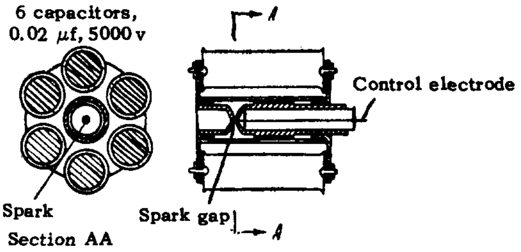

FIG. 2. Diagram of a discharge circuit with capacitors in parallel.

Let us examine now several methods used to obtain a low-inductance connection between the capacitor and the spark-discharge gap. Figure 1 shows schematically the arrangement of a dismountable spark lamp, proposed by Früngel.[11] A bushing-type capacitor is placed inside the metal case of the lamp, whose walls serve to carry the current. Light from the spark is transmitted through a plexiglass cylinder. Kovaszney[12] describes a circuit in which a block of 6 capacitors connected in parallel surrounds the discharge gap, as shown in Fig. 2. The capacitors are interconnected with metallic plates. Light passes through a 0.5 mm diameter hole in the electrode. A shortcoming of such a light source is the small angle of light emergence. Vanyukov et al.[8] developed a dismountable pulsed lamp with ceramic capacitors, which emits light at an angle of 120°. In this lamp (Fig. 3) a capacitor bank with a total capacitance of 0.022 μf is charged to 28 kv and then discharged into a circuit with an inductance of 0.06 microhenry. The lamp can withstand prolonged operation at an average power up to 4 kw.

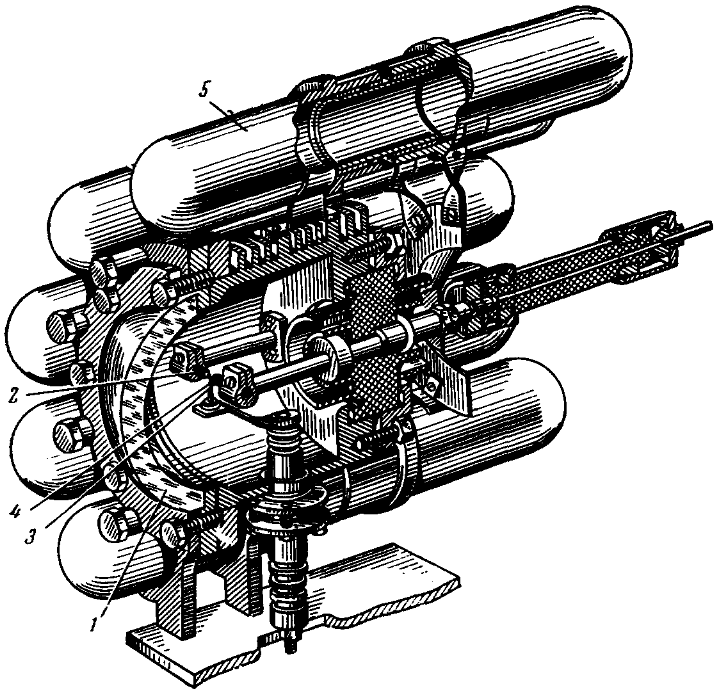

FIG. 3. Dismountable pulse lamp; 1) exit window, 2 and 3) principal electrodes, 4) control electrode 5) ceramic capacitors.

High-intensity short flashes can be obtained by discharging a long line with distributed capacitance and inductance, charged to a high voltage, through a spark gap.[17-19]

We know that if such a line is discharged into a matched load, it delivers to the load a rectangular current pulse, whose duration is equal to twice the time that it takes the wave to travel through the line. In view of the fact that the spark gap does not have a constant resistance during the discharge, it cannot be matched to the characteristic impedance of the line. However, it is advisable in any case to use a line with a low characteristic impedance, for it is well known that after the breakdown the resistance of the discharge gap is a fraction of an ohm. Fitzpatrick et al.[19] used as such a line a segment of a coaxial cable with barium titanate as the dielectric. In view of the high dielectric constant of the barium titanate ($\epsilon \cong 1000$) the characteristic impedance of the cable is only 1.2 to 1.5 ohms. The cable is made in the form of a section of a hollow cylinder with inside and outside diameters 2.5 and 5 cm. The inside and outside surfaces are silver

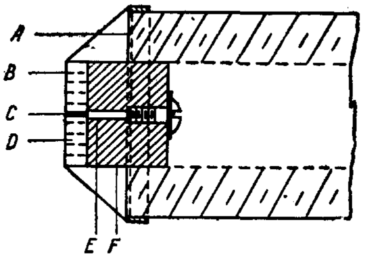

FIG. 4. Discharge circuit with coaxial cable; A) $BaTiO_3$ cylinder, B) steel electrode, E) tungsten electrode, C) discharge gap 0.3 mm in diameter, D and F) insulators.

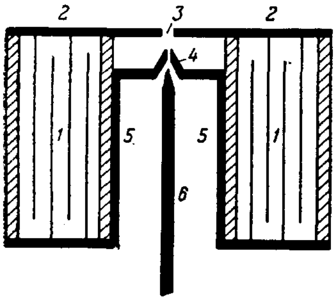

FIG. 5. Discharge circuit with coaxial capacitor, 1) coaxial capacitor, 2) metallic plate with aperture, 3, 4) electrodes, 5) metal tube, 6) control electrode.

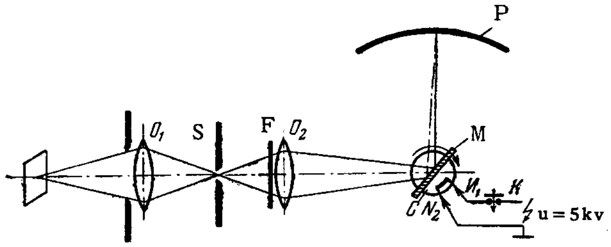

FIG. 6. Optical diagram of photochronograph used to record the glow of explosions.

plated (Fig. 4) and are connected to the discharge gap. A cable 16.5 cm. long is used to obtain light flashes of 10^{-7} sec duration.

The light source described above does not produce, however, high-intensity flashes for to increase the capacitance of the discharge circuit it becomes necessary to increase the length of the cable, which in turn increases the duration of the discharge. This difficulty is overcome by using as the working capacitance a short but multilayered coaxial cable, in which the corresponding electrodes are interconnected in paralle. A schematic diagram of a discharge circuit with such a capacitor, as proposed by Fischer,[15] is shown in Fig. 5. With a capacitance of 0.1 μf and 3 kv applied, the inductance of this circuit is merely 0.004 microhenry. Fischer also reports[16] the development of a toroidal capacitor for a higher voltage ($C = 0.6$ μf, $U_0 = 60$ kv, $L = 0.14$ microhenry), so constructed that it surrounds the discharge gap coaxially.

A low-inductance discharge gap for the production of large pulsed currents has been developed by V. S. Komel'kov and G. N. Aretov.[20] They used flat massive connections for the capacitors and reduced to a minimum the distance between bus bars; they thus succeeded in constructing a discharge circuit comprising 48 capacitors, with a total capacitance of approximately 134 μf at a working voltage of 50 kv, and with a total inductance (disregarding the load inductance) of nearly 0.025 microhenry. The maximum current in such a circuit reaches 2.1×10^6 amp with $(di/dt)_{max} = 2 \times 10^{12}$ amp/sec.

We have already mentioned the principal methods of obtaining spark discharges in which a high rate of power intake is produced by reducing the inductance of the discharge circuit to the limit. Another way of accomplishing the same purpose is to produce the discharge at the highest possible voltage. This method was used by Magan and Woerner[21] to produce a spark discharge with a capacitor of 300μμf charged to 450 kv. The discharge capacitance was that of the electrodes themselves. Owing to the great length of discharge gap a high voltage discharge has a good light efficiency. The radiation from such a discharge was studied in a special chamber, filled with argon and nitrogen at pressures up to 20 atmos. Depending on the pressure, the duration of the light flashes varied from 0.3 to 1.0 μ sec.

I. 2. Methods of Measuring the Brightness and Temperature of Pulsed Light Sources

The measurement of the instantaneous brightness characteristics of pulsed light sources involves considerable experimental difficulties. These are due primarily to the short duration of the radiation process. Fischer[15] and Vanyukov et al.[22] investigated light flashes with a front duration of approximately 10^{-7} seconds. Consequently the apparatus intended for recording the time variation of the radiation intensity of short light flashes should have a very small time constant. The apparatus used in some cases has a time resolution of 10^{-7} to 5×10^{-8} seconds.[22,23,24]

The apparatus used to measure the absolute values of the brightness of pulsed sources is usually calibrated with the aid of standard sources of known brightness or color temperature. The sources employed are incandescent lamps,[22,23,25,26] zirconium lamps,[15] and the sun.[24,27] Of all these sources, the sun has the highest intensity, but its temperature is approximately 6000°K, while that of pulsed sources frequently exceeds 20,000 or 30,000°K. This reduces the measurement accuracy, which depends on the ratio of the temperatures of the standard and investigated sources.[24]

The first measurements of the temperature of pulsed sources of light were made by Anderson and Smith.[25,28] The measurement apparatus, described in reference 25, consists of a monochromator, thermocouple, and galvanometer. The apparatus is calibrated with a comparison lamp. The galvanometer operates as a ballistic instrument when recording the pulsed signal. The brightness of the source, averaged over the flash duration, is determined from the reading of the galvanometer and from the effective duration of the light flash. The

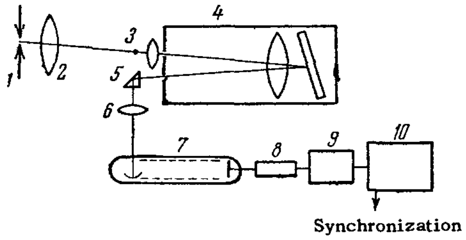

FIG. 7. Schematic diagram of the photoelectric setup used to measure the brightness of a spark-discharge channel.

duration of the light flash is determined by the author from photographs of a mirror scan of the flash. Considering that the effective duration of the signal was estimated rather roughly, the accuracy of brightness measurement by this method is probably not very high.

Later on the brightness and the temperature were measured either by photographic[24,27] or by photoelectric methods.[4,11,15,22,23,26,29,30,31,32]

As an example of the use the photographic method for measurement of instantaneous values of the temperature, we refer to a paper by I. Sh. Model'[24] on the determination of the temperature reached in shock compression of gases.

The optical system of the apparatus, comprising a high speed photochronograph with a rotating mirror, is shown in Fig. 6. Slit S passes over part of the image of the investigated event which is focused in the plane of the slit by objective O_1. The image of the slit is projected by objective O_2 on the photographic plate P after being reflected by the rotating mirror M. Filter F comprises jointly with the photographic film a simple monochromatizing system ($\Delta\lambda \approx 900$A). The exposure time can be adjusted from 10^{-5} to 10^{-7} seconds. The same setup was used to photograph the blackening markers produced by the standard, in this case the sum. To permit the use of the reciprocity law, the film exposure time did not exceed 10^{-5} seconds when calibrating with the standard. This was accomplished by using a shutter of the focal plane type. The temperature was measured in this setup with an accuracy of 6 to 20 percent, depending on the absolute values of the measured temperature.

It must be noted that the photographic procedure for brightness measurement has several shortcomings, the major one being the low sensitivity. Furthermore, the processing of the results is complicated and labor consuming.

The photoelectric method of brightness measurement is much more sensitive. The radiation receivers usually used in this method have a very high time resolution (up to 10^{-8} or 10^{-9} sec), and the processing of the measurement results is quite simple and takes little time. In the first experiments the time variation of the light intensity of the flashes was recorded photoelectrically. The brightness of the channel was determined from these data with allowance for the effective area of the glowing substance.[11,30] A shortcoming of the method is that it can be used to determine only the brightness averaged over the channel. Furthermore, its accuracy is low owing to errors in the determination of the area of the glowing substance.

The first to measure directly the brightness of a discharge channel in pulsed lamps were Vanyukov et al.,[22] who used the photoelectric method. The schematic diagram of the measuring setup is shown in Fig. 7. A small portion of the glowing substance of the lamp 1 is projected by lens 2 on the plane of the entrance slit of monochromator 4. The bandwidth of the monochromator is 26 A. The uniformly illuminated objective of the monochromator is projected on the cathode of the photomultiplier 7 by lens 6. The output signal of the photomultiplier passes through delay line 8 and is applied to amplifier 9, and then to the plates of oscillograph 10. The time resolution of the photoelectric system amounted to 7×10^{-8} seconds. The sensitivity of the system was regulated by introducing neutral attenuation filters. Owing to the spatial instability of the discharge channel, it was impossible to record with this method the time variation of the brightness of the brightest portion of the glowing substance within a single discharge. Consequently 100 to 150 oscillograms of the flashes were photographed and the oscillograms with maximum signal amplitudes were selected.

The sensitivity of the apparatus was calibrated with the aid of an incandescent lamp ($T = 2073$°K). A rotating-mirror arrangement made it possible to use modulated light for the calibration. The procedure described produces wavelength vs. spectral energy density curves for the brightest portion of the glowing substance for various instants of time. These data afford a most complete description of the brightness and can be used to determine the visual brightness and the effective brightnesses for other selective radiation receivers (photographic film, photocells, etc.).

An analogous procedure for the measurement of the brightness of pulsed sources of light is used in references 23, 26, 29, 31 and 32.

In another interesting procedure, recently described by Fischer,[15] the instantaneous value of the visual brightness of pulsed sources is determined directly. The radiation is picked up by a photomultiplier, the output signal from which is recorded with an oscillograph. Narrow spectral filters are used, maximum transmission at

$\lambda = 5450$ A. The standard used is a dc zirconium lamp with a visual brightness of 4050 c/cm². A rotating disk transforms the dc-light signal from the standard source into a pulsed signal, whose duration is comparable in length with that of the pulsed source. Neutral attenuation filters are used to reduce the amplitude of the signals from the pulsed source. The visual brightness B of the investigated light source is obtained from the expression

$$B = B^* \cdot \frac{S}{S^*} \cdot \frac{f}{D} \ \mathrm{c/cm^2},$$

where B* is the brightness of the standard lamp, S the amplitude of the pulsed-lamp signal, S* is the amplitude of the standard-lamp signal, D is the transparency of the attenuating filters, and f is a color factor that takes into account the difference in the spectral emission of the investigated and standard lamps.

The color factor f is determined by the author from the following relations:

$$f = \frac{U^*}{U} \cdot \frac{b}{b^*};$$

$$U = \int E_\lambda T_\lambda Z_\lambda \, d\lambda;$$

$$U^* = \int E^*_\lambda T_\lambda Z_\lambda \, d\lambda;$$

$$b = \int E_\lambda V_\lambda \, d\lambda;$$

$$b^* = \int E^*_\lambda V_\lambda \, d\lambda,$$

where E_λ is the relative spectral radiation density of the pulsed lamp, E^*_λ the relative spectral radiation density of the standard lamp, T_λ the transmission of the filters, Z_λ the relative spectral sensitivity of the photomultiplier, and V_λ the relative spectral eye sensitivity.

In the author's opinion, the error in f did not exceed 5 percent, and the error in the visual brightness B did not exceed 10 percent (concerning the results obtained by the author, see Sec. I.3).

To understand the physical processes in the spark-discharge channel, and in particular to ascertain whether it is possible to increase its brightness, it is important to determine the temperature of the discharge channel. Since the processes connected with the spark discharge are highly non-stationary, such terms as temperature, equilibrium state, etc. are evidently not applicable to a light-emitting plasma.[33] References 33 to 37 are devoted to the problems that are raised thereby.

S. L. Mandel'shtam and N. K. Sukhodrev have shown[36] that the excited states of the atoms in the spark-discharge channel have a Boltzmann distribution, while the ionization is given by the Sach formula. In both cases the role of temperature is played by the electron temperature. The excitation distribution becomes stationary within approximately 10^{-10} sec, and the ionization becomes stationary within 10^{-7} sec. The time required for the electron and gas temperatures to become equalized is also approximately 10^{-7} sec. It is shown in reference 37 that in the plasma of the spark-discharge channel the relation between the radiating and absorbing ability of the radiator is given by Kirchhoff's law, provided the temperature of the latter is taken to be the electron temperature. It was also shown[38,39] that the Boltzmann distribution holds for the excited atoms in the plasma of the spark-discharge channel if the gas pressure is not less than 100 mm Hg. It was established in references 22, 23, 29, 31, and 32 that at certain discharge conditions the spectral distribution of the emission of the spark-discharge channel follows roughly that given by Planck for a black body.

It has thus been established at present that the plasma of the spark-discharge channel can be assigned a definite temperature if the time exceeds 10^{-7} sec. For time durations less than 10^{-7} seconds the emission of the spark discharge is determined by the electron temperature of the plasma. This must be borne in mind in cases when the plasma temperature is determined from the emission of the spark-discharge channel.

Having made these remarks we can proceed to a brief description of the existing methods for determining the temperature of the glowing substance in pulsed-light sources. The brightness method of determining the temperature was used in references 23, 24, 29 and 32. In this method the brightness of the investigated body is compared with that of a standard of known temperature, determined from the following expression[24]

$$\frac{\left(e^{\frac{e_2}{\lambda T}} - 1\right)}{\left(e^{\frac{e_2}{\lambda T_0}} - 1\right)} = \tau a,$$

where T_0 is the temperature of the standard, T the temperature of the investigated light source, λ the effective wavelength of the employed spectral interval, τ the ratio of the brightness of the standard to the brightness of the investigated body, a the absorption coefficient of the investigated body, and $c_2 = 1.438$ cm-deg.

This method is used most frequently in those cases when it is established somehow that the absorption coefficient of the glowing body is unity.[23,29,32] Under certain conditions (brightness "saturation") the temperature can be measured by the brightness method using not only continuous but also line-spectrum radiation.[23]

Babushkin[40] and Glaser[41] use a color method for determining the temperature, in which the spectral distribution of the unknown body and of a black body are compared. It must be kept in mind, however, that this method is less accurate than the brightness method at high temperatures ($> 10{,}000°$ K).[24]

If the plasma of the discharge channel is transparent the temperature can be determined from the ratio of the intensities of two spectral lines.[37,39,42,43] The temperatures are determined from the relation

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \nu_1}{A_2 g_2 \nu_2} e^{\frac{E_2 - E}{kT}},$$

where I_1 and I_2 are the line intensities, A_1 and A_2 are the transition probabilities, g_1 and g_2 are the statistical weighting factors of the above terms, ν_1 and ν_2 are the frequencies of the lines, E_1 and E_2 are the excitation energies of the above levels, k the Boltzmann constant, and T the unknown temperature.

It must be borne in mind that to determine the maximum temperature in the discharge channel it is necessary to use lines of highly-ionized atoms, and also to time-scan the spectrum.[42,43]

Various non-optical methods of temperature determinations are also used. Thus, in references 28 and 40 the temperature is determined from the sound velocity, using the following relation

$$v = \sqrt{\frac{\gamma RT}{m}},$$

where v is the sound velocity in a medium of temperature T, R is the gas constant, γ is the ratio of the specific heats, and m is the molecular weight.

Since the molecular weight is also a variable quantity at high temperatures, this equation must be solved simultaneously with the Sach equation.

V. S. Komel'kov and D. S. Parfenov[44] use the following expression from the pinch-effect theory[45] to determine the plasma temperature of the spark-discharge channel

$$2NkT = I^2,$$

where I is the current of the discharge, N the total number of particles per centimeter length of the channel, k Boltzmann's constant, and T the average gas temperature in the channel.

Simultaneous solution of this equation with the Sach equation yield the temperature T.

Several other methods for measurement of the spark-discharge channel temperature are discussed in reference 41.

I. 3. Maximum Brightness Obtained with the Aid of a Spark Discharge in Gases

The first systematic investigations of optical characteristics of the spark discharge in an atmosphere of various gases were made by Glaser in 1950-1951.[4,41] In particular, he investigated the brightness of the spark-discharge channel in an argon atmosphere by mirror scanning. By photometry of the resultant photographs Glaser has established that the maximum instantaneous brightness along the axis of the discharge channel increases with increasing power supply to the channel only up to a certain limit.[4,41] Further increase in the power leaves the brightness unchanged at a value corresponding to the brightness of a black body at a temperature of approximately 40,000° K.[41]

K. S. Vul'fson, I. Sh. Libin, and F. A. Charnaya[46] used an analogous procedure for a systematic investigation of the brightness of the spark-discharge channel in atmospheres of argon, krypton, and xenon at various gas pressures and at various discharge energies. The authors have also reached the conclusion that the brightness of the discharge channel in these gases reaches a limit with increasing voltage. It was established that the voltage at which the limiting brightness is reached depends on the type of gas and on its pressure. Thus, for example, at a gas pressure of two atmospheres the limiting brightness in xenon is reached at a discharge-circuit voltage of 5 kv, in krypton at 6 kv, and in argon only at 10 kv. As the pressure increases, the maximum brightness is reached at lower voltages.

The effect of brightness saturation was investigated by Vanyukov, Mak, and Parazinskaya,[22] and also by Vanyukov and Mak,[23] who used a photoelectric procedure to register the time variation of the spectral brightness density of the central portion of the channel in energy units. Using this procedure, Vanyukov et al.[22] investigated the continuous radiation from a spark discharge in argon and xenon at pressures of 4 to 5 atmos in the spectral region from 4000 to 9000 A, with a time resolution of 0.07 μsec and with a spectral resolution of approximately 26 A. They also investigated the influence of the inductance of the discharge circuit on the brightness of the channel. A change in the inductance of the discharge circuit affects greatly the energy intake by the spark-discharge channel,[47] and therefore a study of the affect of the inductance

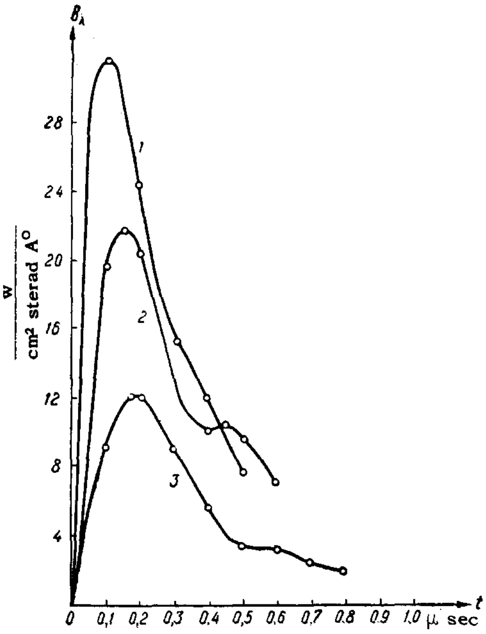

FIG. 8. Time dependence of bλ of the discharge channel in argon for various values of circuit inductance; 1) 0.12 microhenry, 2) 0.6 microhenry, 3) 1.1 microhenry; $\lambda = 4680$ A, $U_0 = 12$ kv, $C = 0.011$ μf.

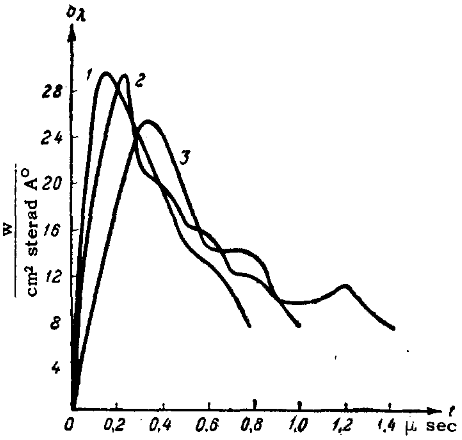

FIG. 9. Time dependence of bλ of the discharge channel in xenon for various values of circuit inductances: 1) 0.12 microhenry, 2) 0.6 microhenry, 3)1.1 microhenry; $\lambda = 4490$ A, $U_0 = 12$ kv, $C = 0.011$ μf.

on the spark-channel brightness is of substantial interest.

Figures 8 and 9 show typical curves for the dependence of the spectral brightness density b_λ in the central portion of the channel on the time t for various values of the inductance of the discharge circuit for discharges in argon (Fig. 8) and in xenon (Fig. 9). It was established that the brightness saturation is easiest to obtain in the long-wave portion of the spectrum. As the radiation wavelength decreases, the maximum brightness is obtained at lower inductance values. By way of an example, Fig. 10 shows the variation of the maximum instantaneous spectral brightness density of the spark-discharge channel in an argon atmosphere with the inductance of the discharge circuit for various wavelengths. In the case of discharge in xenon maximum channel brightness was obtained over the entire investigated spectral region even when the maximum circuit inductance was used.

It was also established that when the maximum brightness is reached, the radiation from the discharge gap closely approximates the radiation of a black body with a temperature determined from the value of the spectral density of the discharge-channel brightness. Figure 11 shows the spectral variation of b_λ of a discharge in xenon for various instants of time lapsed since the beginning of the discharge. The figure shows that at the instant $t = 0.1$ μsec the discharge radiation corresponds to that of a black body at $T = 27{,}000$°K.

The maximum brightness of the spark-discharge channel in argon exceeds the maximum brightness of the channel in xenon, although the brightness of xenon lamps is higher than those of argon at slow rates of energy intake by the discharge channel (Fig. 12).

Vanyukov and Mak[23] extended the investigation of the continuous background of the brightness spectrum into the ultraviolet region of the spectrum (to 2300 A), and also investigated the line-spectrum radiation from ionized gases in which a discharge was produced. This investigation has shown that with increasing discharge-circuit in-

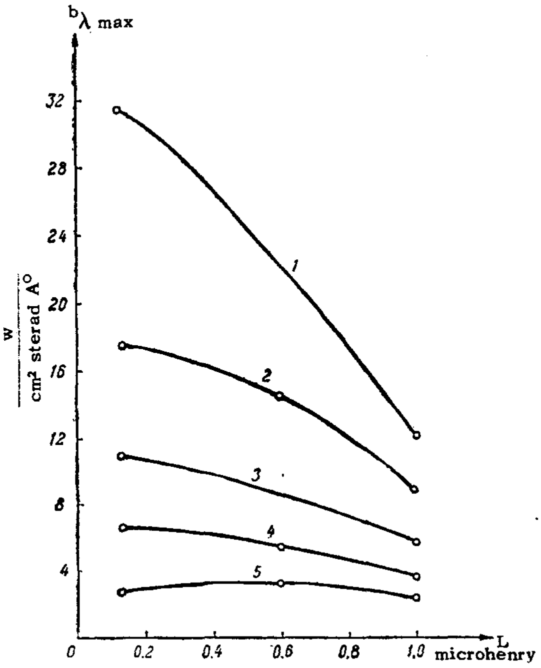

FIG. 10. Dependence of bλ of the discharge channel in argon on the discharge-circuit inductance for various wavelengths: 1) 4,680 A; 2) 5540 A; 3) 6520 A; 4) 7230 A; 5) 8870 A.

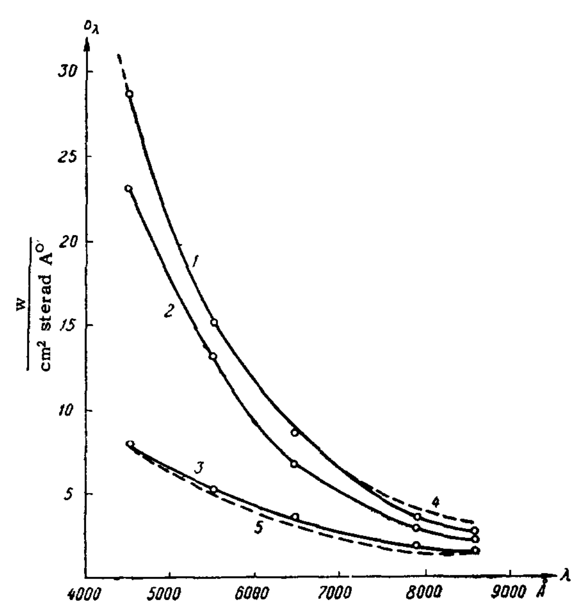

FIG. 11. Dependence of bλ of the discharge channel in xenon on the wavelength for various instants of time: 1) 0.1 μ sec, 2) 0.3 μ sec, 3) 0.8 μ sec, 4 and 5) bλ of a black body at 27,500°K and 14,500°K, respectively.

ductance the line-spectrum radiation intensity reaches a maximum more rapidly than the intensity of the continuous background, owing to the large absorption coefficient of the plasma in the lines. At the same time the temperatures, determined from the maximum value of the spectral brightness density of the continuous and line radiation are in good agreement, thus confirming the conclusion made in reference 22 that as brightness saturation is reached the discharge channel radiates like a black body. The degree of correspondence between the radiation of the spark-discharge channel and the radiation of a black body is illustrated in Fig. 13, which shows the wavelength dependence of the temperature for discharges in argon, xenon, and nitrogen. From the temperature values shown in the diagram it is possible to determine with the aid of Table IV (see Sec. VI) the value of the maximum visual brightness. In accordance with reference 22, it amounts to 11×10^6, 15×10^6, and 21×10^6 c/cm² for xenon, argon, and nitrogen respectively.

F.A. Charnaya investigated the dependence of the spark-discharge channel brightness in air,[48] xenon, krypton, argon, oxygen, nitrogen, neon, and helium[26] on the breakdown voltage, on the gas pressure, and on the distance between the electrodes (absolute brightness values were measured in reference 26). In all these gases, with the exception of helium, the author has established that the spark discharge channel reaches maximum brightness. When the discharge is formed in air[48] the maximum

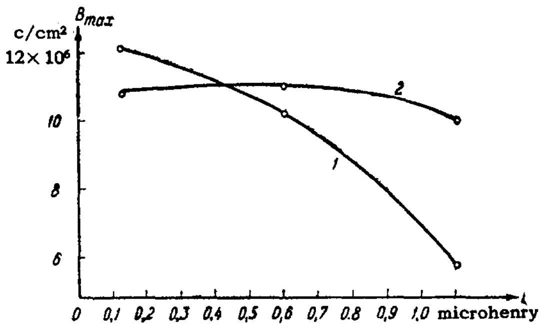

FIG. 12. Dependence of the maximum instantaneous brightness of the channel of the inductance of the discharge circuit: 1) argon, 2) xenon.

brightness was seen to increase with pressure in a range up to 7 atmos. The maximum brightness remained unchanged when the distance between electrodes was varied from 1.5 to 6 mm. It was also found that the maximum brightness of the discharge channel in air exceeds the maximum brightness in argon at the same pressure. Reference 26 also states that as the atomic weight of the gas decreases, the maximum brightness increases thus confirming the results of reference 22 for argon and xenon.

A study of the dependence of the value of the maximum brightness on the pressure of the filling gas[26] has shown that at sufficiently large pressures the maximum brightness is independent of the pressure.

Fischer[15,16,49] has investigated the visual brightness of a spark-discharge channel in air and helium, the discharge being produced in a circuit with very small inductance (L = 0.004 microhenry, C = 0.1 μf). The maximum brightness found in air was 45 to 50×10^6 c/cm². In helium at p = 35 atmos

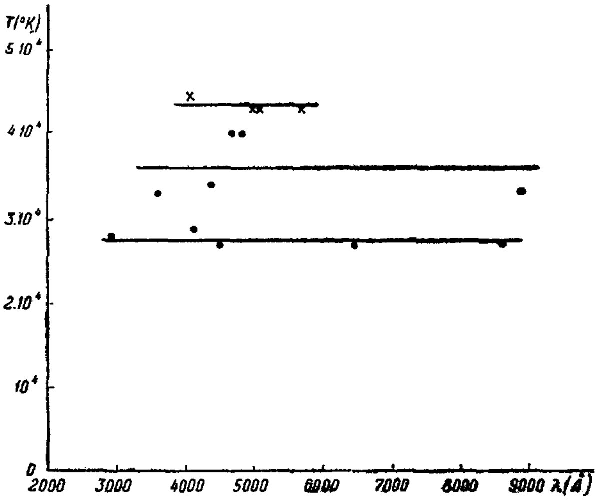

FIG. 13. Temperature of the spark-discharge channel in xenon, (●), argon (○) and nitrogen (×), C = 0.05 μf, L = 0.086 microhenry, U_0 = 12 kv (for argon and xenon), and U_0 = 15 kv (for nitrogen).

TABLE I

Gas	Temperature, °K	Visual brightness, c/cm²	Authors, reference
Xenon		1.7×10^{8}	Früngel[11]*
	27 000	1.1×10^{7}	Vanyukov, Mak, and Parazinskaya,[22] Vanyukov and Mak[23]
Argon	140 000	2×10^{8}	Früngel[11]*
	40 000		Glaser[41]
	35 000	1.5×10^{7}	Vanyukov and Mak[23]
	37 000		Model'[24]
Air (nitrogen)		5×10^{7}	Fischer[15]*
	43 000	2.1×10^{7}	Vanyukov and Mak[23]
	44 500		Charnaya[26]**
		4×10^{8}	Edgerton and Cathon[50]*
Helium	250 000	1.5×10^{8}	Fischer[15]*

*In our opinion these results are too high.

**Calculated from the maximum brightness cited in this paper for λ = 9000 A.

and U = 7 kv (maximum discharge current I = 63 kilo amperes, discharge energy W = 68.5 joules) the maximum brightness was on the order of 150×10^6 c/cm^2, corresponding to a temperature of T = 250,000°K. This is apparently the highest temperature registered in a spark-discharge channel. It must be noted, however, that the maximum brightness for air, measured by the same author, disagrees with the results of reference 23, where it has been established that the temperature of the spark-discharge channel in nitrogen is 43,000°K, corresponding to a maximum visual brightness of 21×10^6 c/cm^2.* It can therefore be assumed that Fischer's values of brightness and temperature of a spark-discharge channel in helium are too high. There is no doubt, however, of the fact that a spark discharge can produce a much greater brightness in helium than in air.

From an examination measurements that are the most reliable from our point of view, we can conclude that for each gas there exists a limiting brightness, which can be obtained with a spark discharge of sufficient power.

The maximum brightness is reached most easily in gases having low ionization potential.

Table I gives a summary of the values of temperature and of visual brightness obtained with spark discharges in atmospheres of various gases.

I. 4. Physical Limitations on the Brightness of the Spark-Discharge Channel

An investigation of the emission of the spark-discharge channel and of the distribution of the brightness of the glowing substance, and measurement of the transmission coefficient of the discharge-channel plasma, have shown that in the brightness saturation mode the discharge channel is opaque and radiates as a black body (in those portions of the spectrum where saturation is reached).[4,15,22,23] In connection with this, a hypothesis has been set forth in references 15 and 26, that the existance of a maximum brightness is related to the opaqueness of the spark-discharge channel at high temperatures.

A similar point of view was set forth by Ya. B. Zel'dovich[51,53] and developed by Yu. P. Raizer[52] in connection with the radiation from strong shock waves. Taking into account the strong dependence of the radiation absorption coefficient on the temperature (the Kramers formula was used to estimate the absorption coefficients of air at high temperatures), the authors have concluded that at high temperatures there is formed in front of the shock wave a heated zone that begins to shield the radiation travelling from the front of the wave. According to calculations,[52] the heated layer of air shields completely the outward radiation even when the temperature behind the shock wave front

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*The temperature of the spark-discharge channel in nitrogen, obtained from the value of maximum brightness at λ = 9000 A as found in reference 26, is approximately 44,500°K, which is in good agreement with the results of reference 23.

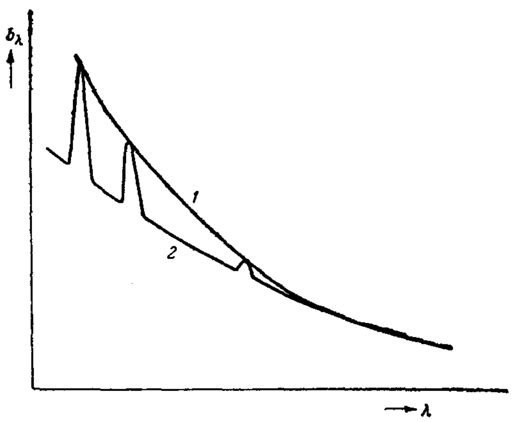

FIG. 14. Dependence of b_λ of the spark-discharge channel on the wave length for the case of total (1) and partial (2) brightness saturation.

is on the order of 9×10^4 °K, and the brightness of the shock wave front, after passing through a maximum, drops to a value corresponding to an approximate temperature of 1.8×10^4 °K.

It must be noted, however, that the theoretically predicted[51] brightness maximum has not yet been observed experimentally.

To check the applicability of the concepts developed by Zel'dovich and Raizer to the spark-discharge channel, it becomes very important to study the temperature distribution over the cross section of the channel. For this purpose Vanyukov and Mak[23] investigated the discharge-channel brightness for those cases which the channel plasma is partially transparent in certain regions of the spectrum. At the same time, they studied the spectral brightness density b_λ of the continuous and line radiation for varying rates of energy intake by the discharge channel. Owing to the large absorption of radiation by the plasma in the lines of the ionized atoms of the gas, maximum brightness is reached for line radiation more readily than for continuous radiation. Figure 14 shows schematically the channel-brightness spectra of a spark discharge for total brightness saturation over the entire spectrum (curve 1) and for the case when b_λ reaches a maximum value only in the line spectrum and the long-wave spectral region (curve 2).[23] The temperature, determined from the maximum value of b_λ of line-spectrum radiation, was in good agreement with the temperature determined from the maximum value of b_λ of continuous radiation. These results give grounds for assuming that the temperature distribution over the spark-discharge channel cross section does not differ greatly from a uniform distribution. Actually, taking into account the strong temperature dependence of the absorption coefficient of the plasma[52] it can be expected that were a region with higher temperature than that of the "screening" layer to exist inside the channel, the lines of the ionized atoms would be self-reversed or else would be observed in absorption.[*] It must be noted that G. G. Dolgov and S. L. Mandel'shtam,[55] on the basis of an examination of the gas density distribution in the spark-discharge channel, also reached the conclusion that the temperature is constant over the cross section of the channel.

The absence of considerable temperature gradients in the current-conducting discharge channel is apparently related to the considerable heat conduction (radiant and electronic) of the discharge plasma at temperatures on the order of 3 to 4 times 10^4 °K.

It also follows from the results of reference 23 that the temperature of the spark-discharge channel is independent of the rate of energy intake by the channel and is approximately equal to 27,000°K, 35,000°K and 43,000°K for xenon, argon, and nitrogen respectively. The temperature values obtained for nitrogen are in good agreement with the discharge temperature determined spectroscopically from the intensity ratio of two spectral lines,[36] a method that can be applied only in the absence of noticeable reabsorption in the channel, i.e., in cases where brightness is far from being saturated.[†] One can therefore assume that a spark-discharge channel of constant temperature is maintained over a very wide range of variation of energy intake by the discharge channel.

The foregoing experimental results give grounds for assuming that the brightness saturation of the spark-discharge channel is related not to the screening of the high-temperature discharge zones by the cooler ones, but to the presence of a maximum channel temperature. The existance of a maximum temperature for a given gas can be explained qualitatively from energy considerations. As the channel temperature increases there is, on the one hand, an increase in the power intake due to increased ionization and radiation. On the other

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[*] The radiation absorption spectrum of a spark discharge may show lines of neutral atoms.[54] In this case the absorption layer is the shell of the current-conducting channel, heated by the passage of the shock wave to a temperature on the order of 10^4 °K. This zone absorbs very little of the continuous radiation in the visible region of the spectrum, particularly during the time of the maximum brightness.

[†] In reference 43 the ratio of the intensities of the lines Si IV were used to determine the channel temperature of a low-voltage spark in air ($U = 200$ v, $C = 1000$ μf, $L = 10^{-6}$ to 10^{-3} henry). It was found to equal approximately 30,000°K. Considering that the temperature determined in this investigation was averaged over the glow time of the Si IV lines, the agreement with the results of reference 23 is satisfactory.

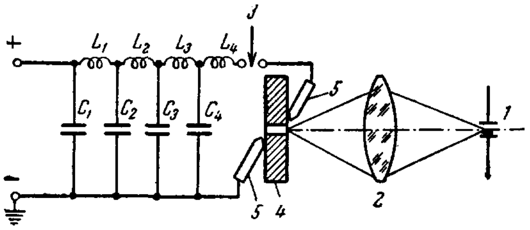

FIG. 15. Circuit diagram of a capillary spark discharge. $C_1 = C_2 = C_3 = C_4 = 100\ \mu f$, $L_1 = L_2 = L_3 = L_4 = 1.5$ microhenry. 1) slit of the spectrograph, 2) condenser, 3) spark-discharge control switch, 4) textolite plate with an opening, 5) electrodes.

hand, the increased ionization of the channel plasma lowers the resistance, causing the energy entering into the discharge channel to be reduced.[56] Effects in the same direction are obtained when the discharge-channel diameter is increased upon increase of its energy intake;[6] and also in the increase of heat conduction of the plasma at high temperatures. All this makes it impossible for the power absorbed per unit volume of the plasma channel to increase indefinitely, and this in turn limits the temperature of the channel of an open spark discharge.* It must be noted, however, that the mechanism by which the brightness becomes saturated in a spark discharge cannot yet be considered as finally established.

II. SPARK DISCHARGE IN CAPILLARIES

From the point of view of producing a high instantaneous brightness, a spark discharge with a channel is bounded by the walls of a capillary tube is of particular interest. The energy density in a so confined discharge channel can become very large, and consequently high temperatures and brightnesses can be produced in the channel. Another advantage of the capillary discharge is that the glowing substance is stable in space, an important factor in many measurements. The capillary discharge is used in optical shadowgraphic and interferometric apparatus[13,19,59] and others.

Among the first papers devoted to an investigation of high-brightness capillary spark discharges, mention should be made of that of Anderson.[25] He discharged a 1 to 2 μf capacitor at 35 kv in a tubular lamp up to 30 cm long and 0.1 to 2 cm in diameter. The tube was evacuated to pressures of the order of 1 cm Hg. The discharge was therefore produced essentially in an atmosphere of the vapor of the wall material

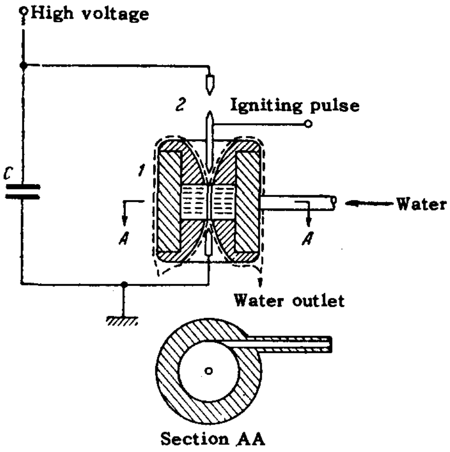

FIG. 16. Setup for producing a capillary spark discharge in a water turbine.

(silicon). The maximum temperature measured by the author amounted to 52,000°K.

Edgerton and Cathon[50] report the development of a xenon capillary pulsed tube, with channel brightness up to 10^7 c/cm^2 at flash durations from 0.3 to 3 μsec, depending on the discharge circuit parameters. The capillary is 1.2 mm in diameter and 6 mm long. The tube is made of quartz and can withstand up to a thousand flashes without a substantial reduction in the light output.

M. P. Vanyukov, A. A. Mak, and M. Ya. Ures[31] report that when a circuit with 0.011 μf capacitor charged to 29 kv is discharged into a capillary 0.4 mm in diameter, the temperature reaches 94,000°K.

N. N. Ogurtsova and I. V. Podmoshenskii[29] have developed a pulsed light source with a brightness that stays constant during the pulse (approximately 100 μsec). They used for this purpose the discharge of an artificial transmission line through an opening in a textolite plate. The arrangement is shown in Fig. 15. The capillary was 2 mm in diameter and 10 mm long. The artificial transmission line consisted of four identical sections with C = 100 μf, L = 1.5 microhenry. The discharge voltage was 3 kv. The characteristic impedance of the line (R = 0.12 ohm) was matched to the resistance of the spark gap. The light pulse in such a discharge had an almost rectangular form, and the brightness temperature measured by the authors was 32,000°K.

A. A. Mak[32] describes a pulsed light source in which the spark discharge is produced in a cavity bounded by a water wall. The advantage of such a light source is that it can withstand very powerful discharges for an unlimited time interval without damage. A schematic diagram of the setup is shown in Fig. 16. Water enters into a turbine 1

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*From this point of view it is interesting to note the statement made in several papers[35,57,58] that the current density in channels of open spark discharges reaches a limiting value.

TABLE II

Type of discharge	Gas	Gas pressure (atmos)	Discharge voltage (kv)	Capacitor rating (μf)	Capillary diameter (mm)	Temperature (10^3 °K)	Visual brightness (10^6 c/cm^2)
Capillary	Air	1	12	0.011	1.3	29	8
"	"	1	12	0.5	1.3	64	39
"	"	1	12	0.011	0.4	48	18
"	"	1	12	0.011	0.25	36	16
"	"	1	29	0.011	0.4	94	50
Open	"	1	12	0.011	—	23	7
Capillary	Xenon	4	12	0.011	2.5	23	7
Open	"	4	12	0.011	—	27	11

in a direction tangent to the wall at a pressure of 1.5 to 2 atmos. The centrifugal forces produce a cylindrical cavity along the axis of the turbine, with a diameter that is determined essentially by the diameter of the apertures in the end walls of the turbine. The air spark gap 2 serves to prevent production of an arc discharge in the capillary. The discharge circuit has a capacitance of 0.05 μf and an inductance of 0.1 microhenry. At a discharge voltage of 18 kv, the channel temperature reaches 60,000° K, corresponding to a visual brightness of 33×10^6 c/cm^2.

The optical properties of the plasma of a capillary discharge channel are investigated in references 25, 29, 31, 32, 40, 50, 60 and 61. Comparison of the channel brightness as observed from a direction parallel to the axis of the discharge and from a direction perpendicular to the axis of the discharge has shown that at temperatures higher than 40,000° K, the absorption coefficient of the channel plasma is close to unity even at thicknesses on the order of 0.05 mm.[32] That the discharge column is opaque is established also in references 25, 29, and 60. A study of the spectral distribution of the continuous radiation from a capillary discharge has shown[29,31,32] that at sufficiently large energy densities the channel radiates as a black body, whose temperature can be determined from the spectral brightness density of the channel.

Of great physical and practical interest is the question of the maximum temperatures and brightnesses that can be reached in a capillary spark-discharge channel. References 31 and 32 report on a study of the effect of the discharge circuit parameters and also of the capillary diameter on the temperature and brightness of the discharge channel. Table II lists the measurement results obtained in reference 31.

It has been established that higher temperatures and brightnesses can be obtained in a bounded spark-gap channel than in an open discharge. However, for each discharge mode there exist a certain optimum capillary diameter, at which the channel brightness has a maximum value. If the channel is either excessively or insufficiently constricted, its brightness decreases. When the energy intake by the discharge channel increases, the brightness and temperature increase but at a rate that slows down with increasing energy (Fig. 17).[32] This latter circumstance may be caused, in addition to a considerable increase in the specific heat of the gas at high temperatures, also by intense evaporation of the capillary walls in the case of powerful discharges. The influence of the wall material on the radiation from a capillary spark discharge has been investigated in references 52, 60, and 62 to 64. Weltner[64] investigated, in particular, the influence of the capillary-wall material on the intensity of the continuous radiation at a gas pressure of approximately 1 mm Hg in the capillary and at current densities of the order of 4×10^4 amp/cm^2. He established that the emission intensity is independent of the gas pressure if the amount of evaporated wall material exceeds the amount of gas that fills the capillary.

It is shown in reference 29 that at current densities on the order of 4×10^5 amp/cm^2 the radiation spectrum remains unchanged as the gas pressure is reduced from 1 atmos to 1 mm Hg. The authors of this paper have therefore reached the conclusion that the discharge originates primarily in the wall-material vapor, and that the pressure of this vapor may reach 500 atmospheres. We can thus assume that the amount of evaporated wall material increases with increasing current density

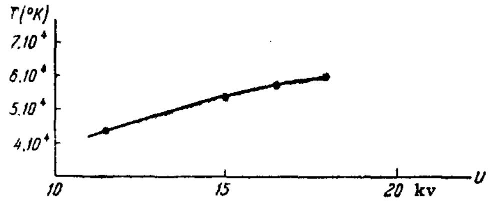

FIG. 17. Dependence of the temperature of a capillary spark discharge channel on the discharge voltage. C = 0.05 μf, L ≅ 0.1 microhenry, d = 0.5 mm.

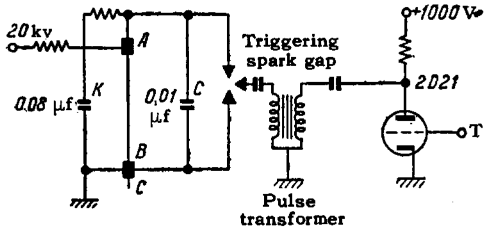

FIG. 18. Schematic wiring diagram of the guided-spark generator, the "Defatron."

in the capillary. This, on the one hand, entails a large amount of energy for evaporation, dissociation and ionization of the vapor, and on the other hand makes it difficult for the energy to enter into the discharge channel, owing to the sharp increase of pressure in the capillary. These considerations give grounds for assuming that the principal factor that limits the temperature and brightness of the spark-discharge channel in a capillary is the evaporation of the capillary walls. However, this problem must be investigated further.

III. GLIDING SPARK DISCHARGE

The spark discharge in air, the simplest pulsed light source used in high-speed photography for more than a century, yields very brief light flashes (10^{-6} to 10^{-7} seconds) but has a low light output. New light sources developed in the recent two decades, based on the use of the luminescence produced by pulsed electric discharges in heavy inert gases (argon, krypton, and xenon) have a much larger light output, but do not yield flashes shorter than several microseconds in duration. A most interesting source of light is the gliding spark discharge, in which the spark is produced between electrodes located on a surface of a dielectric, so that the discharge gap can be made 10 to 20 times longer than the gap in the ordinary spark discharge, and the light output can be substantially increased.

The gliding spark discharge has been under investigation for a long time (see references 65 to 69), but its use as a source of brief and intense light flashes is relatively recent.[13,70-74]

To facilitate the breakdown of the long spark gaps necessary to obtain a high light output, use is made of the so-called guided spark. This spark, which is used in particular in a spark generator known as the "Defatron" produces a 10^{-6}-sec light flash at a discharge energy of approximately 200 joules and a capacitor voltage of 22 kv.[13] Its operating principle can be seen in Fig. 18. The spark gap consists of two annular electrodes A and B, placed 10 cm apart on a dielectric tube, inside of which is inserted a control electrode C in the form of a rod. A potential difference of 22 kv is applied between electrodes A and B. The discharge is initiated by grounding the electrode C, which is connected through a large resistance to electrode A. The large field gradient produced between the electrodes A and C causes intense ionization of the air at the surface of the tube near electrode A, causing the gap to break down. The control electrode is grounded by means of a 3-electrode spark discharge gap triggered by applying a voltage pulse to the grid of a thyratron. The "Defatron" flash tube has a lifetime from 100 to 300 discharges.

A certain shortcoming of these sources of light, in which a gliding discharge is produced over the surface of the glass tube, is that the spark does not always follow a straight line between the anode and the cathode and may wind itself around the tube and thus partially screen the light. In addition, a light source with a straight long glowing body requires a cylindrical-parabolic reflector to concentrate the light flux, and the use of such a reflector is not always convenient. It becomes therefore advantageous to produce a light source with a more compact glowing body, suitable for use with an ordinary spherical optical condenser system. For this purpose it is necessary to be able to change the trajectory of the discharge path in the desired direction, something that can also be achieved in a guided gliding-spark discharge.

The gliding discharge breaks down along a path in which the ionization is higher than in the surrounding volume. The ionization, other conditions being equal, depends on the thickness of the dielectric between the control and principal electrodes and increases with decreasing thickness. The spark can therefore be guided by cutting a groove in the dielectric layer along the direction of the desired propagation of the discharge. Tawil[74] used synthetic rubber as dielectric and obtained S-shaped and circular discharge trajectories. Such light sources withstood up to 1200 flashes.

In another proposed illuminating device[72,73] the guided discharge is produced over the surface of a tube made of a porous ceramic, impregnated with an electrolyte, in which one end of the tube is inserted. By changing the concentration of the electrolyte it is possible to change the gap resistance. Furthermore, owing to the diffusion of the electrolyte, the characteristics of the gap are automatically restored and its service life is consequently increased. Approximately 90 percent of the energy stored in the discharge circuit is liberated in such a discharge gap. Using a 0.25-µf capacitor charged to 12 kv, a spark-gap length of 5 to 8 cm can be reached. The half-width of the light pulse is 0.9 μsec. The intensity of the flash, as measured by its photographic action, is 5×10^6 candlepower. If the gliding discharge is produced in argon at 1 and 11 atmos, the light output increases (over that in air at atmospheric pressure) 1.5 and 4 times, respectively. However, the duration of the light flashes is also increased.

A spectroscopic investigation of the gliding spark discharge has shown[75] that in weak discharges there is a weak continuous spectrum and a line spectrum. In powerful discharges, the spectra are characterized by greatly broadened lines and by an intense continuous background, which increases with increasing pressure of the gas that surrounds the dielectric.

In conclusion it must be noted that the light characteristics of the gliding spark discharge, in spite of its advantages as a source of short and intense flashes, has not yet been fully investigated.

IV. ELECTRIC EXPLOSION OF WIRES

Intense light flashes can be obtained also when large current pulses flow through thin metallic wires. This changes the wire explosively into a metal vapor in which the electric discharge produces a high-temperature plasma.

The electric explosion of wires, first observed in 1815,[76] is still the object of research and rather lively discussions,[77-87] owing with the rather complicated mechanism by which the metal is converted from its solid state into a vapor within a very short time (10^{-6} to 10^{-7} sec).

The glow associated with the electric explosion of the wire can be used in many cases to produce intense flash illumination. Such a source of light has certain advantages over flash bulbs, for no radiation is absorbed in the walls of the bulb, and more effective use is thus made of the ultraviolet radiation. Furthermore, when exploding a wire it is possible to supply an almost unlimited amount of energy to the discharge and to obtain very high instantaneous values of light flux. Thus, for example, when photographing non-luminous phenomena through a Kerr cell, the flash produced by an electric explosion of a wire has an instantaneous light intensity of 5×10^8 candlepower.[88] An analogous source of light was used successfully in investigations involving pulsed photolysis.[89]

The temperature developed in exploding wires was determined in references 28 and 90. These measurements have shown[28] that the temperature averaged over the volume of the metal vapor cloud is 20,000 to 30,000° K at the instant of time when the expansion of the glowing vapor cloud practically ceases. The method used in reference 28 to measure the vapor temperature of the exploding wire (by determining the speed of propagation of sound waves in the vapor) does not make it possible to estimate the temperature at the early stage of the explosion, since the plasma is opaque during that time.

There is one paper especially devoted to the photometry of the light energy radiated during the explosion of the wire,[91] where the blackening of photographic plates by light from the explosion is compared with that produced by a standard source of light. A shortcoming of this technique is that it does not afford an estimate of the time variation of the radiation, and yields only the average radiation power over a certain effective flash time, the length of which is taken by the author from some other paper. In addition, the paper does not contain an estimate of the actual dimensions of the glowing body, and consequently there is no possibility of using the obtained data to determine the temperature and brightness of the glowing body.

A detailed observation of the time variation of the brightness of the discharge channel in the explosion of wires would be of great interest, since there are grounds for expecting that the metal vapor becomes heated to very high temperatures. Actually, it has been shown by calculation,[81] on the basis of results of direct oscillographic determination of the energy liberated during the explosion, that in the case of the explosion of a silver wire 0.15 mm in diameter and 3 cm long mounted in organic glass, the energy liberated through the discharge of a 10 μf capacitor charged to 7 kv is sufficient to heat the vapor to 150,000° K (disregarding the radiation and ionization losses).

V. SHOCK WAVES

The propagation of strong shock waves in gas is accompanied by an intense glow, the mechanism of which is described, for example, in the thorough survey of Ya. B. Zel'dovich and Yu. P. Raizer.[53]

At the present time the glow of shock waves is used as a pulsed source of light in special explosion lamps, usually filled with argon.[92-97]

The arrangement of one such lamp has been described in reference 96. The lamp is a glass bulb 6.25 cm in diameter, filled with argon. The lamp contains a charge of explosive substance of conical form, with a base diameter somewhat smaller than the diameter of the bulb. The distance between the base of the charge and the end window of the lamp varies from 0.5 to 2 cm and determines the duration of the flash. The lamp

TABLE III

Gas	Temperature, °K		
	Spark discharge	Shock wave	
	Experimental value[23]	Experimental value[24]	Theoretical value[24]
Argon	35 000	34 000	60 000
Krypton	—	33 000	90 000
Xenon	27 000	30 000	106 000

operates in the following manner. An electric detonator mounted at the vertex of the conical charge initiates the detonation of the explosive, and at the instant when the detonation wave reaches the base of the charge a shock wave is excited in the argon and produces an intense glow. The duration of the resultant flash is determined by the time required for the shock wave to cover the distance from the surface of the charge to the surface of the end window of the bulb.

Figure 19 shows the time variation of the light flashes in explosion pulsed lamps filled with argon, for various distances between the charge and the glass. The flash of such a lamp has an instantaneous light intensity of 225 million candlepower at a glow area of 33 cm^2 corresponding to an average brightness of 6.8×10^6 c/cm^2. These data show that the explosion lamps produce very brief and intense light flashes.

I. Sh. Model'[24] measured directly the brightness of the front of strong shock waves propagating in an atmosphere of air or heavy inert gases. His method, photographic photometry of time-scan pictures of the shock waves, made it possible to determine the front temperature from its brightness and to measure simultaneously the propagation speed of the wave front. It is possible to calculate from this speed the temperature that can be attained in shock compression. It follows from theoretical considerations that the highest temperature, and consequently the highest brightness, can be expected on a front of strong shock waves propagating in heavy inert gases.

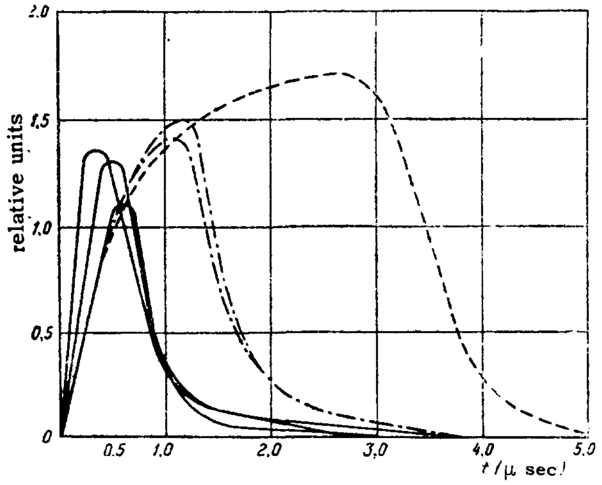

FIG. 19. Dependence of intensity of radiation on the time for flashes of argon explosion lamps. —— Argon layer 0.5 cm thick; —·—·— argon layer 1.0 cm thick; ---- argon layer 2.0 cm thick.

A comparison of shock-wave temperatures calculated from hydrodynamic theory with those determined from the brightness of the front leads to interesting conclusions. The calculated dependence of the temperature of the shock-wave front on the speed of its propagation, taking into account the energy lost to ionization and thermal radiation, is shown in Fig. 20 along with experimental data for argon, krypton, and xenon. The great discrepancy between the theoretical and experimental values of the temperature cannot be attributed to measurement errors, which do not exceed ±20 percent whereas, for example in the case of xenon, the experimental value of the temperature is 3.5 times smaller than the theoretical one. It must also be noted that in contrast to theoretical expectations, the experimental temperature maximum is observed in argon, and the temperature decreases consecutively from argon to krypton to xenon. In his treatment of this interesting phenomenon I. Sh. Model' follows the point of view developed by Ya. B. Zel'dovich and Yu. P. Raizer.[51-53]

Interesting conclusions can be drawn from a comparison of the maximum temperatures produced in heavy inert gases by the propagation of shock waves and by a spark discharge. The values of these temperatures, taken from references 23 and 24, are listed in Table III.

A striking fact is the close agreement between

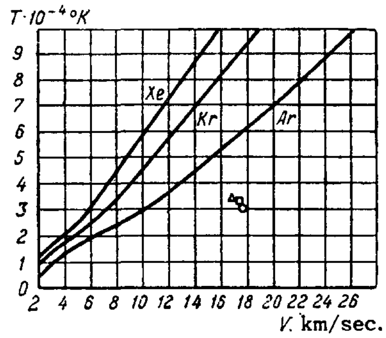

FIG. 20. Temperature of the front of a strong shock wave in inert gases. Experimental values: Δ) argon, □) krypton, o) xenon.

TABLE IV

T °K	$2 \cdot 10^3$	$3 \cdot 10^3$	$4 \cdot 10^3$	$5 \cdot 10^3$	$6 \cdot 10^3$	10^4	$2 \cdot 10^4$	$3 \cdot 10^4$	$4 \cdot 10^4$	$5 \cdot 10^4$	$6 \cdot 10^4$	$1 \cdot 10^5$	$2 \cdot 10^5$
B c/cm²	44,3	$2,83 \cdot 10^3$	$2,34 \cdot 10^4$	$8.41 \cdot 10^4$	$2 \cdot 10^5$	$1,1 \cdot 10^6$	$6,2 \cdot 10^6$	$1,21 \cdot 10^7$	$1.82 \cdot 10^7$	$2,45 \cdot 10^7$	$3.1 \cdot 10^7$	$5.63 \cdot 10^7$	$1,23 \cdot 10^8$

the numerical values of the temperatures measured in the spark-discharge channel and in shock waves. Furthermore, in either case the maximum temperature is in argon and the minimum temperature is in xenon. All this suggests that the plasma produced by electric current has much in common with plasma produced by shock compression, and, apparently, the maximum temperature is the same in either case.

VI. POSSIBILITY OF FURTHER INCREASE IN THE BRIGHTNESS OF PULSED LIGHT SOURCES

The data obtained in recent years on the light-emission characteristics of pulsed light sources permit certain predictions on the possibility of a further increase in the brightness of such light sources.

It must be noted beforehand that the problem of increasing the brightness is essentially a problem of raising the temperature. Table IV gives the dependence of the visual brightness B of a black body on its temperature.

As can be seen from the table, as the temperature of the black body increases the brightness first increases very strongly, and then the increase slows down until, at temperatures above 60,000°K, there is an almost linear relation between the visual brightness and the temperature. Naturally, in addition to having a high temperature, the source of radiation must have also a sufficiently great optical depth in order to produce a high brightness.

The results obtained in references 15, 22, 23, and 26 have shown that maximum brightness that can be obtained in a spark-discharge channel increases with diminishing atomic weight of the gas in which the discharge occurs.*

Consequently, from the point of view of increasing the brightness of pulsed light sources, it becomes of considerable interest to study further the spark discharge in such gases as neon and helium.[15,26] It is also of interest to investigate the temperature and brightness in the spark-discharge channel in other gases, particularly in hydrogen at high pressure.[9]

It must be borne in mind here that the higher the maximum brightness obtainable in a gas, the more difficult it is to produce the discharge conditions under which this maximum brightness is obtainable. Consequently, further improvement in discharge circuits is required, through reduction of the inductance and increase in the discharge voltage. Certain other difficulties must also be overcome in the development of pulsed lamps filled with neon and helium at high pressure.

High temperature and brightness can also be produced in a spark-discharge channel by raising the emitted-energy density. Of interest in this respect is the capillary spark discharge[31,32,50] and the use of the magnetic field of the discharge current to confine the discharge channel.

As regards the capillary spark discharge, further research is needed to increase the brightness of this type of discharge. It is also necessary to study the effect of the wall material of the capillary on the temperature of the discharge channel, and to improve the operating characteristics of capillary light sources.

Limitation of the spark-discharge channel by the magnetic field of its own current (pinch effect), observed in gases at high pressure, is reported in references 44 and 98. Under these conditions one can expect to produce very high temperatures and brightnesses in the spark-discharge channel. However, this problem has hardly been studied hitherto.* Nor have all the potentialities been investigated for increasing the temperature and brightness in the case of shock waves. In particular, it becomes interesting to study the brightness originated in reflection of a shock wave from a barrier, and in

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*There are grounds for assuming that this is related to the increased ionization potential and the investigated gas, not to the atomic weight. In polyatomic gases (N_2, O_2) the dissociation energy apparently also becomes important.

*V. S. Komel'kov and D. S. Parfenov[44] give for the channel temperature a value of 33 electron volts (T = 250,000°K) for a discharge in air of atmospheric pressure.

collision between shock waves.[41,53,98,99] According to theoretical estimates, temperatures on the order of 10^9 °K should be obtainable in these cases.[100]

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