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EXPERIMENTAL STUDIES OF A COAXIAL PLASMA INJECTOR

I. STUDY OF OPERATIONAL CONDITIONS

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I. STUDY OF OPERATIONAL CONDITIONS

EKSPERYMENTALNE BADANIA KOAKSJALNEGO INIEKTORA PLAZMOWEGO
I. OKREŚLENIE WARUNKÓW EKSPLOATACJI

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ КОАКСИАЛЬНОГО ПЛАЗМЕННОГО ИНЖЕКТОРА
I. ОПРЕДЕЛЕНИЕ УСЛОВИЙ ЭКСПЛУАТАЦИИ

Marek Sadowski
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Abstract

The paper describes investigations on the optimization of the parameters and operational conditions of a coaxial plasma injector. A detailed description of the experimental system is given, and the results of measurements performed by means of magnetic probes and a high-speed camera are discussed. The velocities of plasmoids emitted are determined and the regime of efficient operation of the injector is established.

Streszczenie

W pracy opisano badania nad optymalizacją parametrów i warunków eksploatacji koaksjalnego iniektora plazmowego. Podano szczegółowy opis układu eksperymentalnego i omówiono wyniki pomiarów wykonanych przy pomocy sond magnetycznych oraz ultraszybkiej kamery fotograficznej. Określono prędkości emitowanych plazmoidów i ustalono reżim efektywnej pracy badanego iniektora.

Аннотация

В работе описаны исследования над подбором оптимальных параметров и условий эксплуатации коаксиального плазменного инжектора. Приведено подробное описание экспериментальной установки и обсуждены результаты измерений, выполненных при помощи магнитных зондов и сверхскоростной фотографии. Определены скорости генерированных плазмоидов и условия эффективной работы исследованного инжектора.

I. INTRODUCTION

Coaxial plasma guns are common implements serving to produce fast and dense plasmoids. Owing to the considerable number of research works [1 - 11] devoted to such injectors, theoretical foundations have been laid for understanding the mechanism of the processes taking place in them, and an appreciable amount of experimental data concerning different solutions of injector design have been collected.

Despite developing a number of theoretical models and achieving notable consistency of experimental data, many phenomena occurring in the operation of coaxial injectors remain to be explained. There is also not yet available a theoretical description as to provide a basis on which to design an injector of required operational parameters.

On the other hand, in designing experimental installations which involve the necessity of employing plasma injectors, such installations are frequently embraced by certain dimensional and material limitations. In view of the fact that the characteristics of a coaxial gun depend strongly on the design details, each particular injector construction requires thorough operational tests [12] .

The purpose of the present work has been experimental investigation and selection of operational conditions of a small-sized coaxial injector, as also analysis of the parameters of plasma generated.

II. INJECTOR DESIGN AND THE EXPERIMENTAL SYSTEM

A general view of the experimental system is shown in Fig. 1. The external appearance of the investigated coaxial injector is presented in Fig. 2. The electrodes of the injector were made of copper. In investigating the effect of electrode dimensions on the injector characteristics, the diameter of the internal electrode was varied within limits of 8-12 mm, and its active length - within limits of 75-115 mm. The diameter of the external electrode orifice amounted in all cases to 24 mm.

Investigations were concerned with two injector versions only: the type "A" injector with the internal electrode in the shape of a rod, and the type "B" injector with the internal electrode in that of a tube. In the first case, working gas was fed along the gun axis, tangentially to the surface of the internal electrode, in the other - through radial orifices in the internal electrode, situated at a distance of 1/3 of its active length.

The integral part of the plasma gun constituted an electromagnetic fast valve enabling a rapid feeding of a definite amount of gas. As working gas, hydrogen or air was used. Adjustment of the amount of gas fed was effected by varying the pressure of the membrane, or the charging voltage of the condenser bank supplying the winding of the valve electromagnet.

Owing to an axial slit in the valve body and filling it with epoxy resin, the detrimental effect of eddy currents in the body of the injector developed has been eliminated, and the required amount of energy considerably reduced. The capacitance of the auxiliary condenser bank amounted to 8 μF, and with a change of 0.5 - 1 cu.cm in the amount of gas fed /at atmospheric pressure/, the charging voltage varied within limits of 2.5 - 3 kV.

The injector tested was placed at one end of a glass expansion chamber /Fig. 1/ having an external diameter of 8 cm and 60 cm length. The chamber was located inside a solenoid creating a uniform magnetic field B_o = 100 gauss at a section of 25 cm. The other end of the chamber was connected to a vacuum stand equipped with a double-stage rotary pump, an oil diffusion-pump, a nitrogen trap, and auxiliary equipment. The final vacuum value amounted to $p = 8 \times 10^{-7}$ Tr, and the effective pumping rate reached 60 liters/sec /at $p = 10^{-5}$Tr/.

The injector was supplied from a low-induction capacitor $C_n = 1.6\,\mu$F , U_n = 70 kV, that was switched by an air gap and 8 RK-6 concentric cables. As triggered switch, a four-electrode gap with the central electrode on floating potential was used[13]. The high-voltage circuit operated in a pattern of attenuated oscillations with the period T = 6.5 μsec /f = 154 kc/. With the initial voltage U_o = -20 kV, the first discharge-current maximum amounted to 25 kA.

III. METHODS OF MEASUREMENT

To determine characteristics of the injector investigated, a number of measurements were made using magnetic probes, double Langmuir probes and a high-speed photographic camera.

In measurements, external magnetic probes and miniature internal probes, whose design is described in Paper [14] , were employed. The external probes were located on the expansion tube in the area of the uniform magnetic field, at different distances from the injector nozzle: the P_1 probe in a plane $z = 12.5$ cm, and the P_2 probe - in a plane $z = 32.5$ cm. In the chamber space between the probes, deviations from the uniformity of the external magnetic field were not in excess of 5 per cent. Diamagnetic signals accompanying the passage of plasmoids, after being integrated and amplified, were recorded on an OK-17M oscillograph. On the basis of the oscillograms obtained, it was possible to determine the number of plasmoids and the rate of propagation, as also to assess conductivity and electron temperature. The results of the assessment of electron temperature on the basis of analysis of diamagnetic signals and measurements using the Langmuir probe will be described in the subsequent paper. The purpose of the first investigation stage was only to determine the operational conditions of the injectors described above.

IV. SELECTION OF OPERATIONAL CONDITIONS

The operational efficiency of a plasma injector can be estimated on the basis of the amplitude of the diamagnetic signals obtained and the velocity of plasmoids generated, which in turn can be determined from the time-shift of these signals. Since the operational conditions of the injector depend on, among other factors, the geometry of the electrodes, the variations in the diamagnetic signals recorded were investigated as a function of geometric dimensions of the internal electrode. Varying the length and diameter of this electrode, the most advantageous design parameters were chosen. It was established that the diameter of the internal electrode should, in the case of both injectors, amount to 8 mm and its length - 115 mm. Typical oscillograms obtained in these investigations are presented in Fig. 3.

It is commonly known that plasmoids generated in a coaxial injector contain a considerable amount of impurities from residual gas and those derived from materials of insulators and electrodes. In order to determine the character of such impurities in experimental conditions, separate investigations were carried out [15] , and in order to reduce the amount of impurities, the injector internal electrode was so shaped and arranged as to enable plasma to fall directly on the surface of the insulator separating the electrodes.

Apart from the electrode geometry, an essential influence on the operational conditions of a coaxial injector is also exerted by the working gas. Consequently, the dependence of diamagnetic signals on the type and amount of working gas fed /hydrogen or air/ was also investigated. The amplitudes of signals as depending on gas amount are presented in Fig. 4. The most favourable to the injectors investigated proved to be an amount of some 0.5 cu.cm of gas at atmospheric pressure.

One of the most important of the operational parameters of the injector is the delay time τ between the moment of feeding working gas and that of applying high tension to electrodes. As is commonly known, a coaxial injector can operate in two regimes which are characterized by different values of the delay time τ . The first regime occurs with relatively small delays ; the injector then generates at least two plasma blobs: fast plasmoid and slow plasmoid. After increasing the delay time over a certain critical value τ_c , there occurs a transition to the second operating regime, when only the slow plasmoid is generated. Since the principal purpose of injector investigations is generally obtaining pure and fast plasmoids, of primary importance is mainly the first operating regime of the injector. The critical value of the time delay can easily be determined by establishing a decay in the occurrence of the fast plasmoid - for instance, on the basis of signals from the magnetic probes.

With a determined injector design and a definite amount of working gas fed, an essential operational parameter is also the minimum value of delay time τ_{min} , at which there is yet a regular development of discharge in the injector. Time τ_{min} must, of course, be greater than the time of operation of the gas valve. The value τ_{min} can approximately be assessed on the basis of the relation

$$\tau_{min} \approx \tau_v + \frac{l_c + 0.1\, l_e}{\sqrt{\frac{2kT}{m}}} \qquad (1)$$

where τ_v is the time of operation of the fast gas valve,

l_c is the length of the channel through which working gas is fed,

l_e is the length of the internal electrode, and the expression in the denominator corresponds to the most probable value of the velocity of particles /having a mass m and at a temperature T / under the assumption of Maxwellian velocity distribution.

Under experimental conditions, in the circuit of the electromagnetic gas valve, there occurred a strongly attenuated oscillatory current wave having a period $T = 18\,\mu$sec /f=55.5 kc/. This wave was in practice attenuated after two full periods. Hence the approximate time of valve operation amounted to $\tau_v = 35\,\mu$sec. After substituting in the expression (1) the other values characteristic of the experimental conditions investigated, it was calculated that, with air fed /M = 29/, the value of the minimum delay time should, in the case of the type "A" injector, amount to $\tau_{min} = 190\,\mu$sec , and in that of the type "B" injector - to $\tau_{min} = 230\,\mu$sec.

For comparison, the values τ_{min} were also determined empirically. Using a high-voltage divider, variations in the potential of the injector internal electrode in relation to earth potential were recorded. Simultaneously, by means of the Rogowski coil, the current wave in the main discharge circuit was recorded. The two signals were applied to a double-beam OK-17M oscillograph. In the event of delay time τ being too small, there was observed the occurrence of a characteristic voltage signal in the form of a rectangular pulse, and an additional delay in the beginning of the current wave /Fig. 5a/. This indicates that, after applying high tension, the system waited for some time until, as a result of the inflow of working gas, conditions enabling discharge ignition were created. After an appropriate increase in the time delay, a decay of the rectangular voltage signal and a regular discharge development - that is, the occurrence of the beginning of the current wave immediately after applying high tension to the injector - were observed /Fig. 5b/. It should be noted that the accompanying oscillations in the internal electrode potential were not recorded in view of the transmission band of the voltage divider employed. The value τ_{min} thus determined amounted, in the case of the type "A" injector, to 200 μsec, and in that of the type "B" injector - to 240 μsec. From the comparison of the calculated and measured delay times, it follows that the expression (1) gives the value τ_{min} with satisfactory approximation.

From the point of view of injector utilization, the most important is selection of the optimum delay time τ_{opt} at which plasmoids produced have greatest velocities. The value τ_{opt} can be determined, for example, by comparison of diamagnetic signals and the establishment of conditions in which the time-shift of these signals is least /and the amplitude reaches a maximum/. In order to determine the appropriate operating regime for the injectors investigated, a number of such measurements were performed at different time delays in the interval of values $\tau_{min} < \tau < \tau_c$. On the basis of the results obtained, the following values were determined: for the type "A" injector, $\tau_{opt} = 300$ μsec , and for the type "B" injector, $\tau_{opt} = 350$ μsec.

V. INVESTIGATIONS OF THE PROPERTIES OF THE PLASMOIDS GENERATED

Detailed analysis of the oscillograms of diamagnetic signals provided an appreciable amount of information on the number, shape and velocity of the plasmoids produced as depending on the operational conditions of the injectors investigated. The fact was confirmed that in a coaxial injector at least two plasmoids are produced: one, fast, having a velocity in the interval 4 - 5 x 10^6 cm/sec /depending on the design and operational parameters of the injector/, and the other, slower, of a velocity approximatively two times smaller. In some cases, it was also observed the occurrence of a third plasmoid, which was recorded by the probe only in the vicinity of the injector nozzle, and it was not, therefore, possible to determine its velocity. This case will be discussed in greater detail in Part II of the work [16] .

The exact results of measurements of the velocity of plasmoids generated are presented in Fig. 6. The diagram shows the dependence of the velocity of plasmoids on the time delay between the moment of feeding working gas and of the beginning of discharge. To the maximum of the velocity of the two plasmoids, in accordance with the values given above of the optimal delay time τ_{opt}, there corresponds in the case of the type "A" injector the value τ = 300 μsec, and for the type "B" injector - - τ = 350 μsec. It is worth noting that, in the case of application of the type "B" injector, the velocities obtained were of the same order of magnitude as in that of the type "A" injector, but they were some 10 per cent greater than the other in all of the cases observed.

The shape and motions of the plasmoids produced were also investigated by means of an SFR-2M high-speed photographic camera with rotary mirror. The maximum photographing speed of this camera was 2.5 million frames per second. The considerable recording rate of the light beam and the limited active length of the film /37.5 cm/ necessitated an accurate synchronization of the photographing with the discharge process. During the investigations, synchronization /at the moment the rotating mirror attained the appropriate angular position/ was effected by a trigger impulse transmitted from the control unit.

In view of the cylindrical symmetry of the system investigated, the photographs were made in two variants: perpendicular to the axis of the injector and the expansion chamber /with the situation of the camera at the side/ and along the symmetry axis of the system /with the situation of the camera in front of the injector nozzle/. Under experimental conditions, the intensity of plasma visible radiation enabled photographs to be made at a rate not exceeding 1 million frames/sec. The photographs from the high-speed camera enabled determination of the variations in the shape of the plasmoids produced as a function of time and the path passed, as also estimate of the velocity of their propagation. Typical photographs obtained for the type "B" injector, which show plasma motion along the expansion chamber, are presented in Fig. 7. From these photographs, it follows that at least one plasmoid is ejected from the injector. Concerning the motion of this plasmoid, conclusions can be drawn on the basis of the fluorescence of the glass walls of the expansion chamber. The motion of the plasmoid itself is not clearly seen in the photographs due to insufficient density of plasma and the high photographing rate. On the other hand, the luminescence of the chamber walls caused by bombardment of streams of plasma particles is easily noticeable. The rate of plasmoid propagation estimated on the basis of the luminescence observed amounts to about 5×10^6 cm/sec, which is in good agreement with the results of measurements of diamagnetic signals given above. It should be explained that the photographs do not show the second plasmoid /which was recorded by magnetic probes/, since its radiation was even weaker.

Comparison of plasma visible radiation for the two injectors investigated is enabled by resorting to the photographs made in front of the injector nozzle, which are given in Fig. 8. Despite the fact that the discharge conditions were identical, a more intensive radiation of the plasma generated by the type "B" injector is clearly seen. Also clearly visible is the shape of the plasmoid ejected from the injector. Attention should be drawn here to characteristic plasma "protuberances", which are evidence of the occurrence of some instabilities of the plasmoid during its motion in the expansion chamber. In the case of the type "B" injector, it may also be estimated /on the basis of the photographs presented/ the mean velocity of plasma radial motion - it amounts to about 3×10^5 cm/sec, which, as compared with the axial velocity, indicates a marked prevalence of aligned motion.

For comparison of plasma radiation in other operational conditions, given in Fig. 9 is a number of similar photographs obtained for the same injectors, but with an increased amount of working gas /1 cu.cm of air/ and a reduced time delay / τ = 300 μsec/. The less intensity thus obtained of plasma radiation indicates that, in this case, there occurs a deviation from the optimal operational conditions - a fact confirming the results of probe measurements.

It should also be noted that, from the photographs presented in Figs. 8 and 9, it is also possible to determine the diameter of the plasma stream /plasmoid/ in the expansion chamber, where there occurred a uniform magnetic field B_0 = 100 gauss. It is clear that, with such a magnetic field, the plasmoid diameter is only in some cases slightly greater than the diameter of the injector nozzle.

VI. CONCLUSIONS

Consequent on the investigations performed of the effect of the design parameters on the operational efficiency of the coaxial injector, it can be stated that the most advantageous proved to be the case in which the diameter of the internal electrode was three times smaller, and its active length five times greater, than the diameter of the external electrode.

Measurements of diamagnetic signals for plasma injected into a uniform magnetic field confirmed also the fact of the occurrence of at least two plasmoids: a fast, having a velocity $4 - 5 \times 10^6$ cm/sec /depending on the discharge conditions/, and a slow, of a velocity approximately twice smaller. The velocity of the fast plasmoid estimated on the basis of analysis of the photographs obtained from the high-speed camera amounted to about 5×10^6 cm/sec, which yields good agreement of results. It should be noted that, in most of the cases investigated, the velocities of type "B" plasmoids were about 10 per cent greater than those in the case of the type "A" injector.

Evidence of the more efficient operation of the type "B" injector is also found in comparing the plasma photographs made for the two injectors with the camera situated in the symmetry axis of the system. This confirms the observation that, in a coaxial injector, it is more useful to feed working gas throuhg the radial orifices in the internal electrode than tangentially to the surface of such an electrode.

In order to obtain full information on the operation of the injector investigated under experimental conditions determined on the basis of the measurements described, it seems advisable to undertake further investigations of the parameters of plasma generated. The above will be the subject of Part II of the work [16] .

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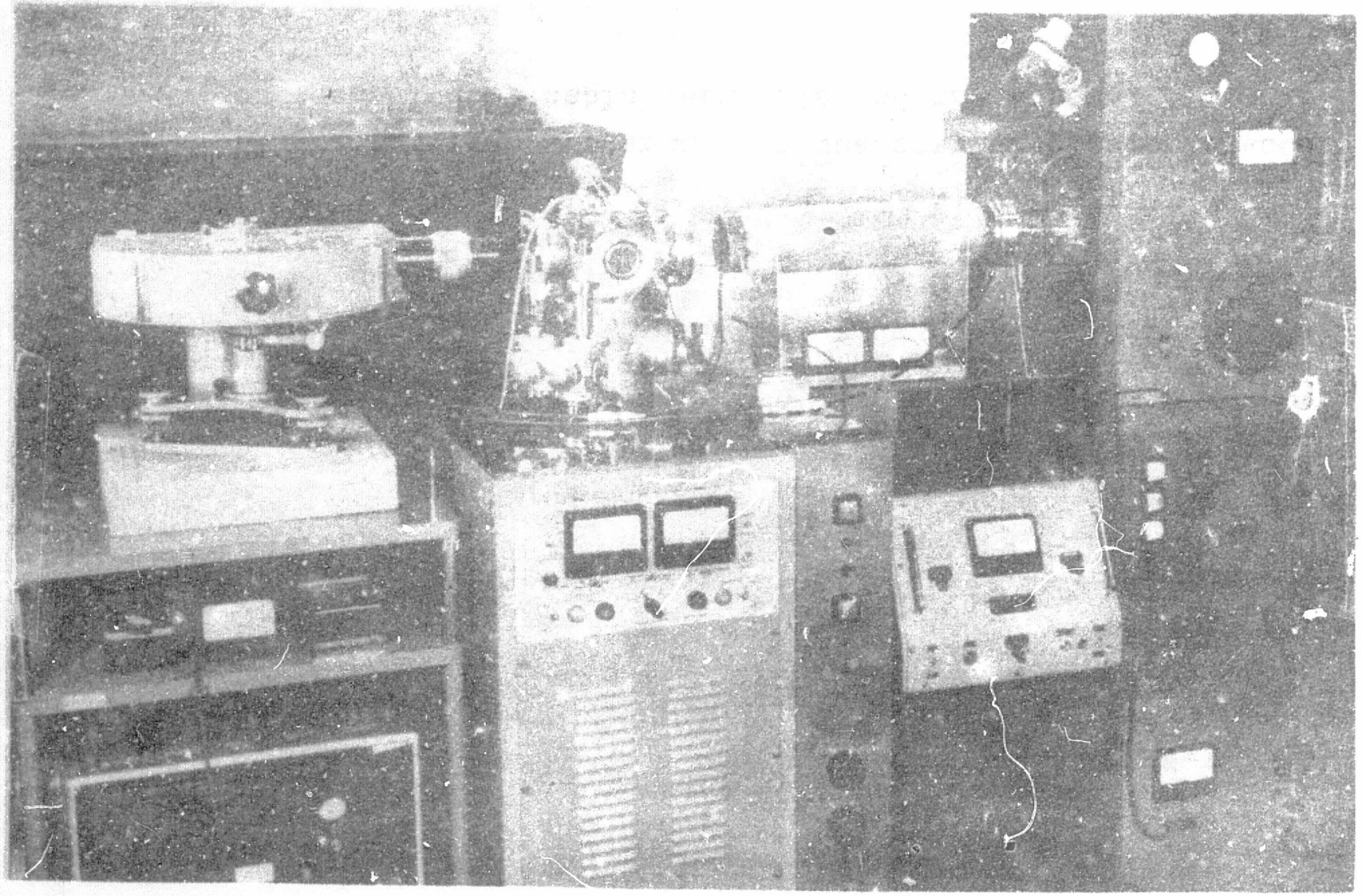

Fig.1. A general view of the experimental system.

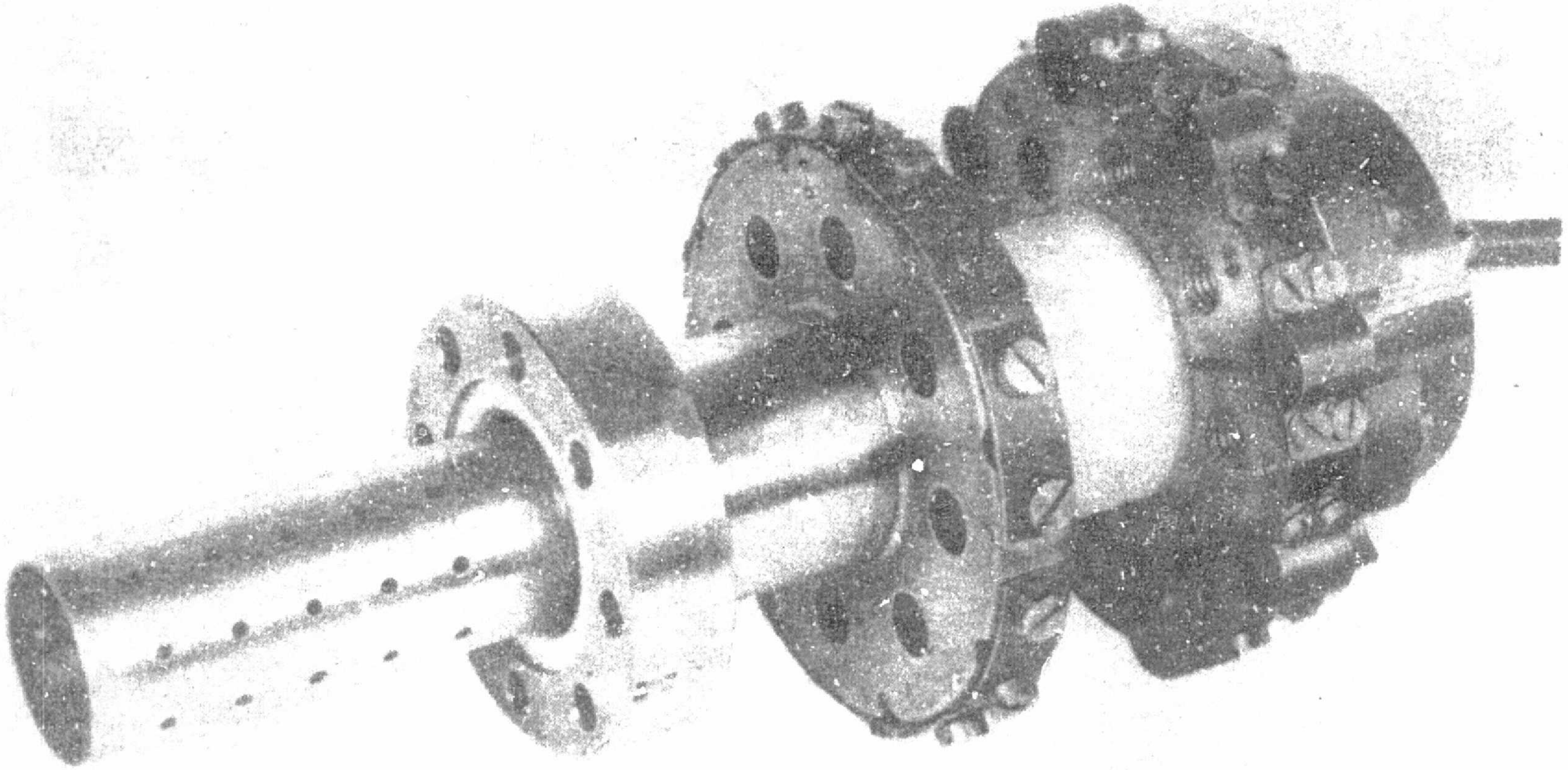

Fig.2. External appearance of the coaxial plasma injector as seen without cable terminals and the screen.

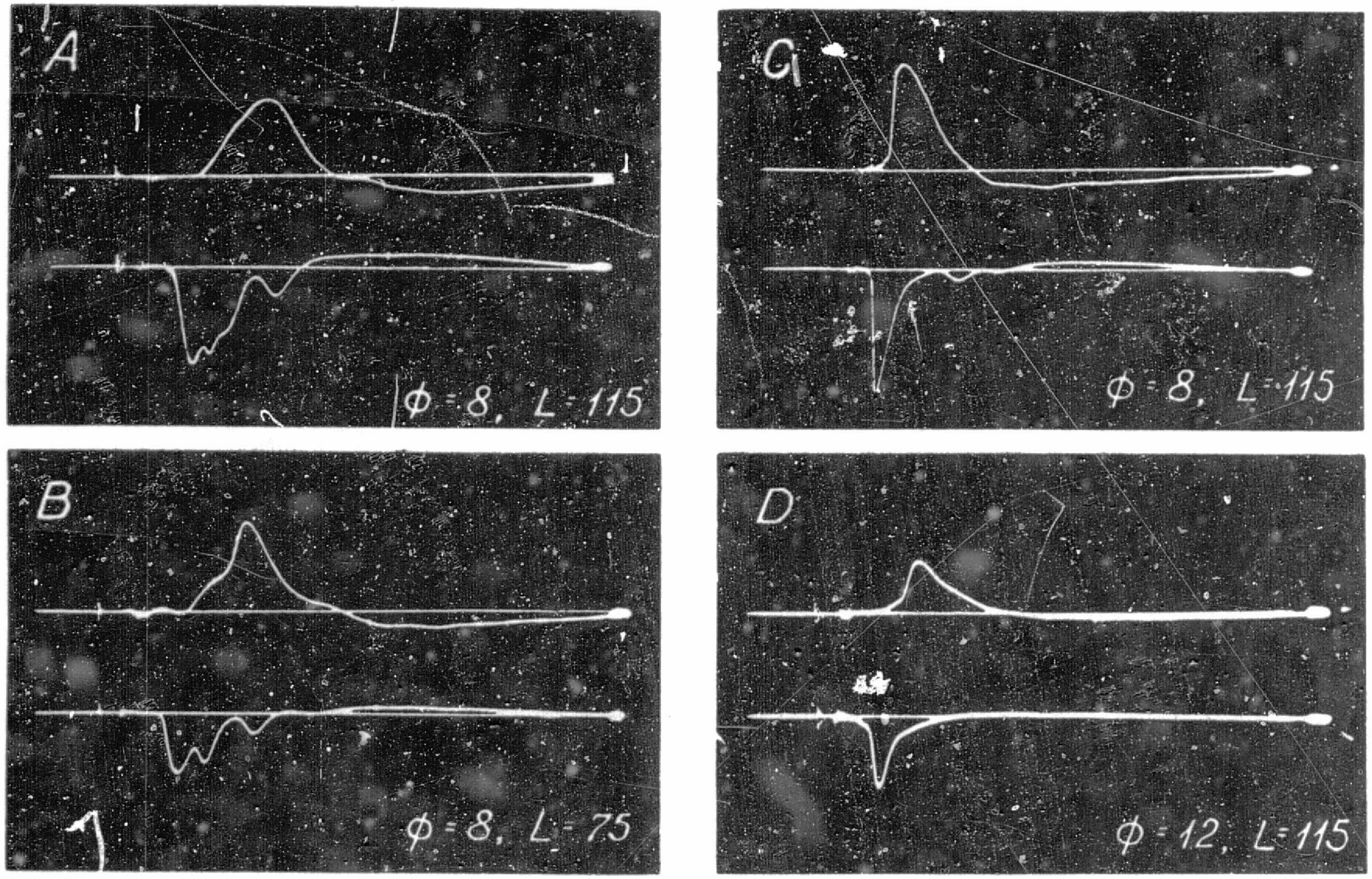

Fig.3. Diamagnetic signals from the 1-st probe /lower traces/ and from the 2-nd probe /upper traces/ as depending on the length and diameter of the internal electrode for the type "A" injector /A,B/ and for the type "B" injector /C,D/. Time-base - 58 μsec.

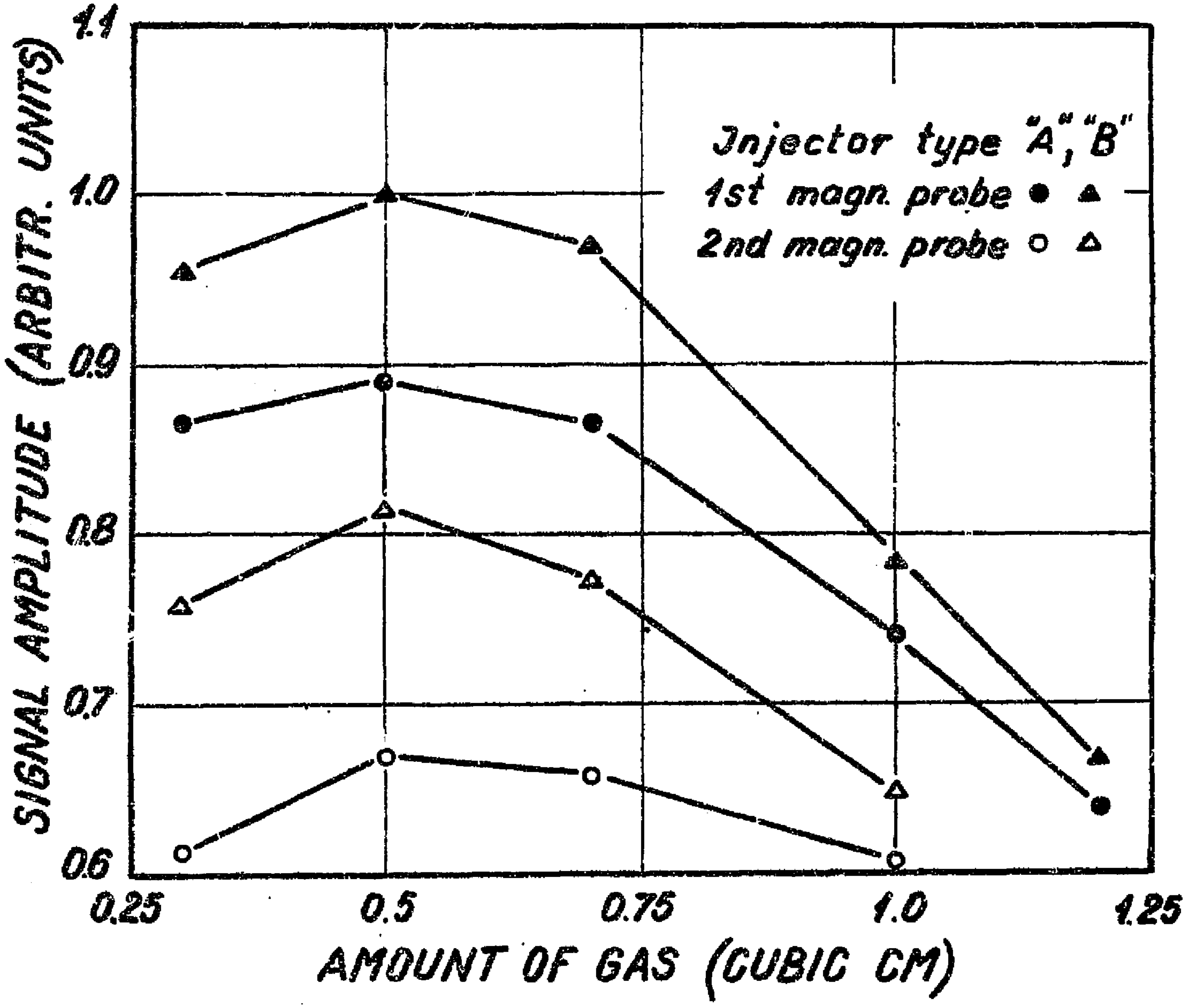

Fig.4. The dependence of the amplitude of diamagnetic signals on the amount of working gas /air/ for various type injectors.

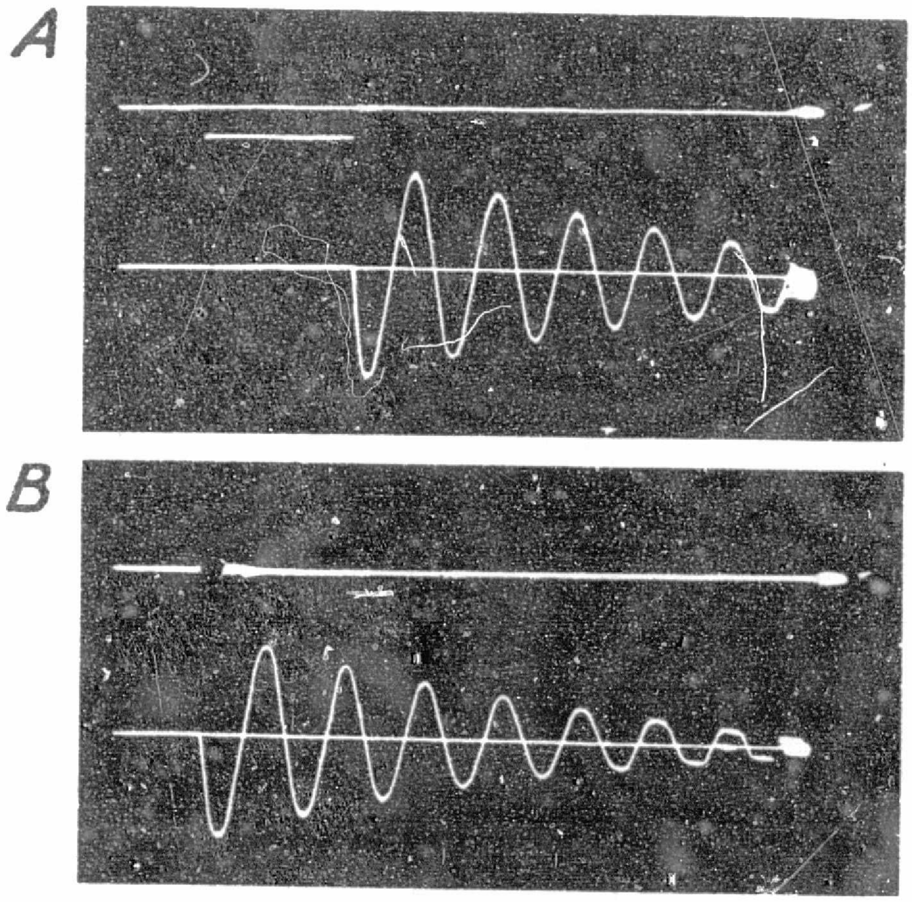

Fig.5. Oscillograms showing variations in the potential of the internal electrode in relation to earth /upper lines/, and current waves in the main discharge circuit /lower lines/ in the case of incorrect /A/ and correct /B/ operation of the system. Time-base 58 µsec.

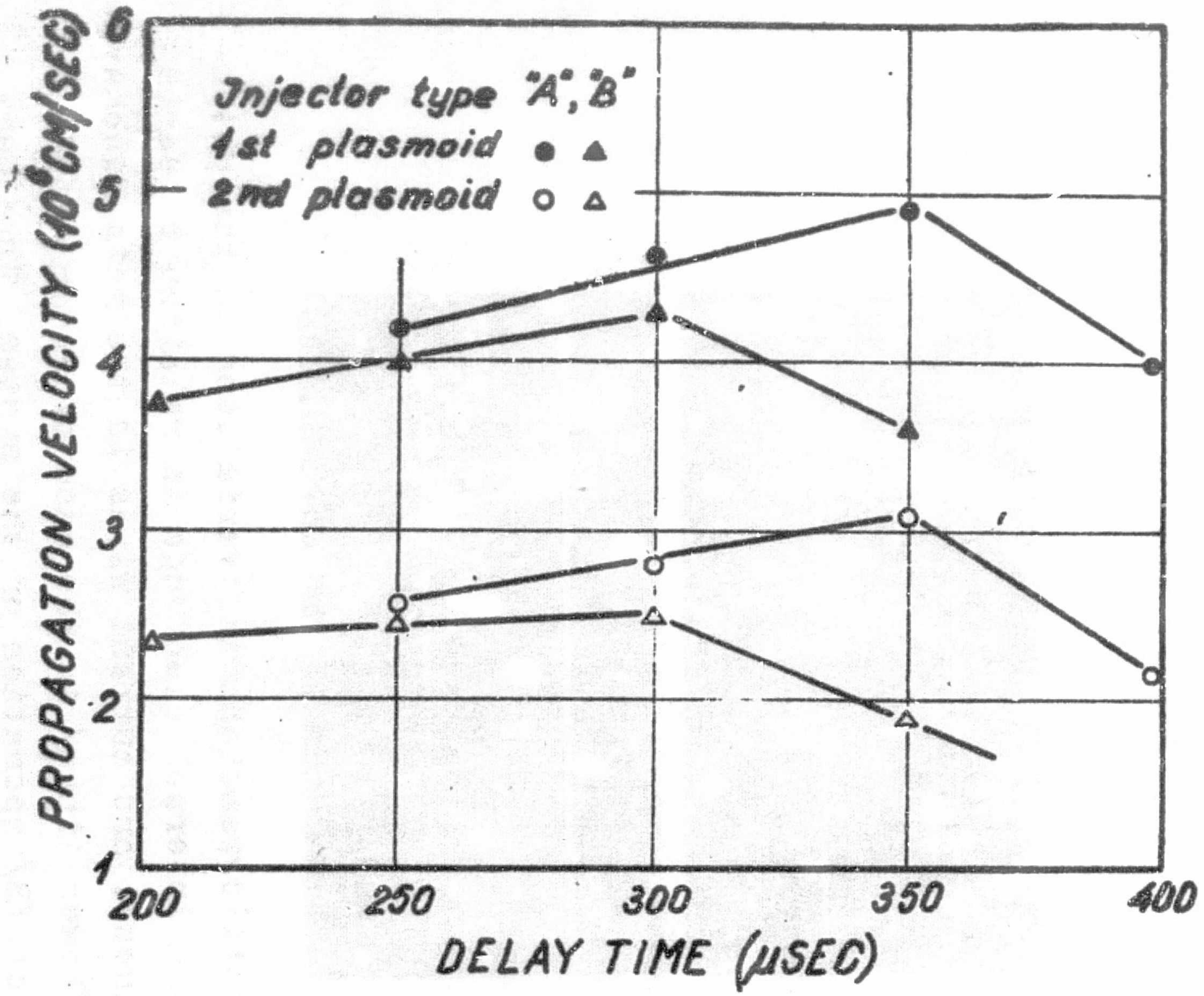

Fig.6. The rate of plasma propagation in the axial direction as depending on the time delay between the moment of working gas feeding and the beginning of discharge.

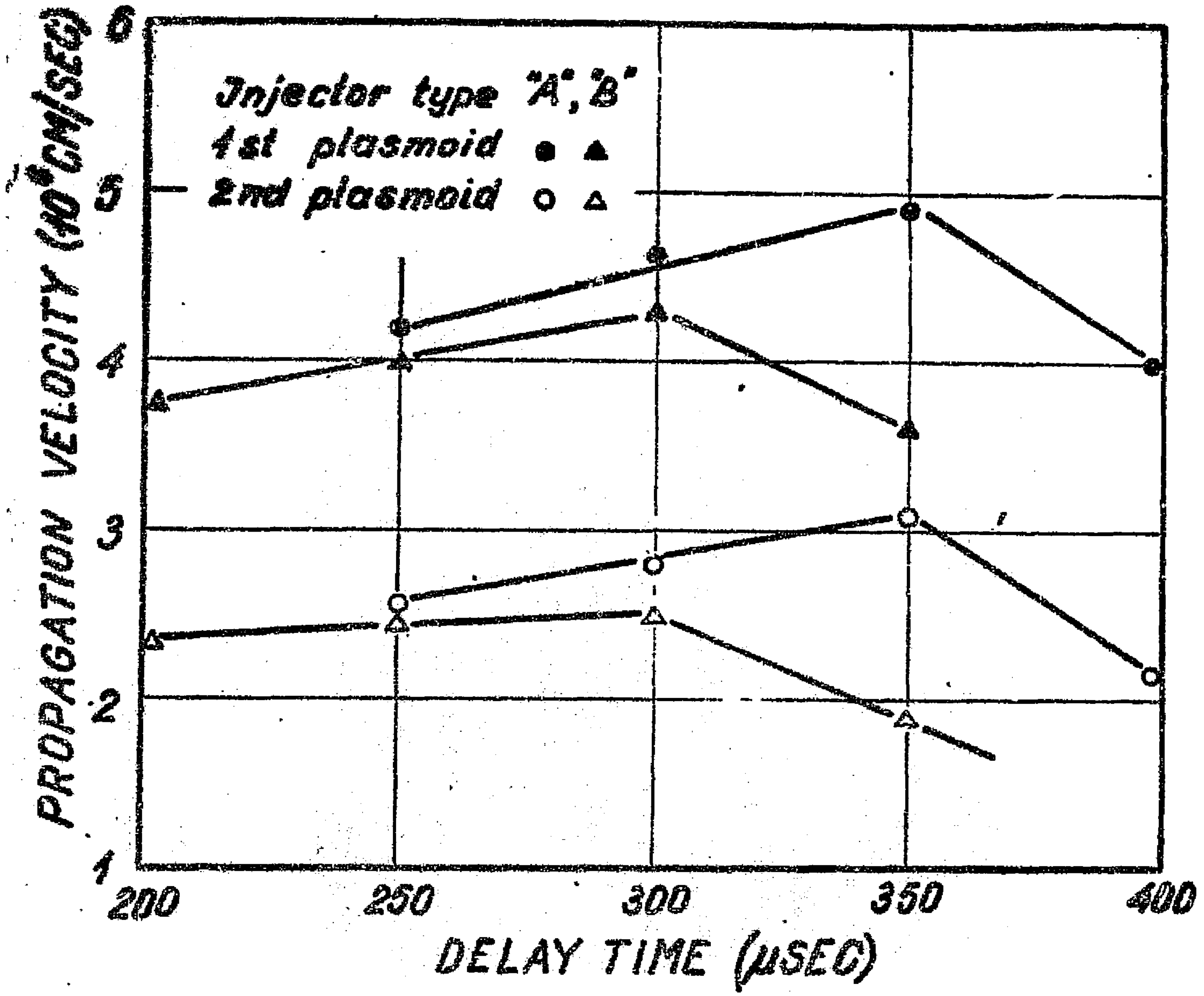

Fig.6. The rate of plasma propagation in the axial direction as depending on the time delay between the moment of working gas feeding and the beginning of discharge.

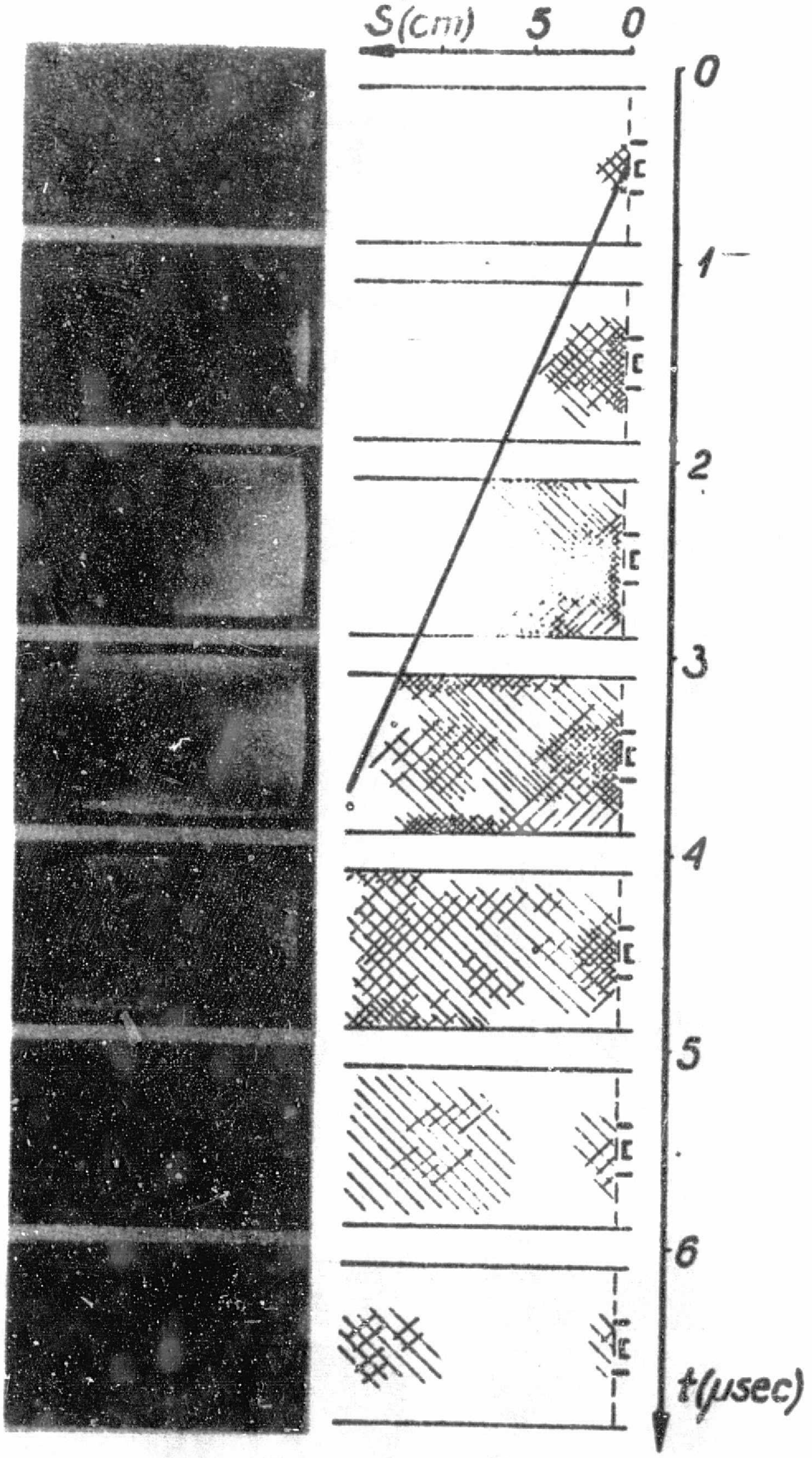

Fig.7. Plasma photographs made by means of the high-speed camera perpendicular to the symmetry axis of the expansion tube. On the right-hand side - a diagram illustrating the phases in plasmoid motion. Discharge conditions: U_0= -20 kV, working gas - air, 0.5 cu.cm, τ = 350 μsec.

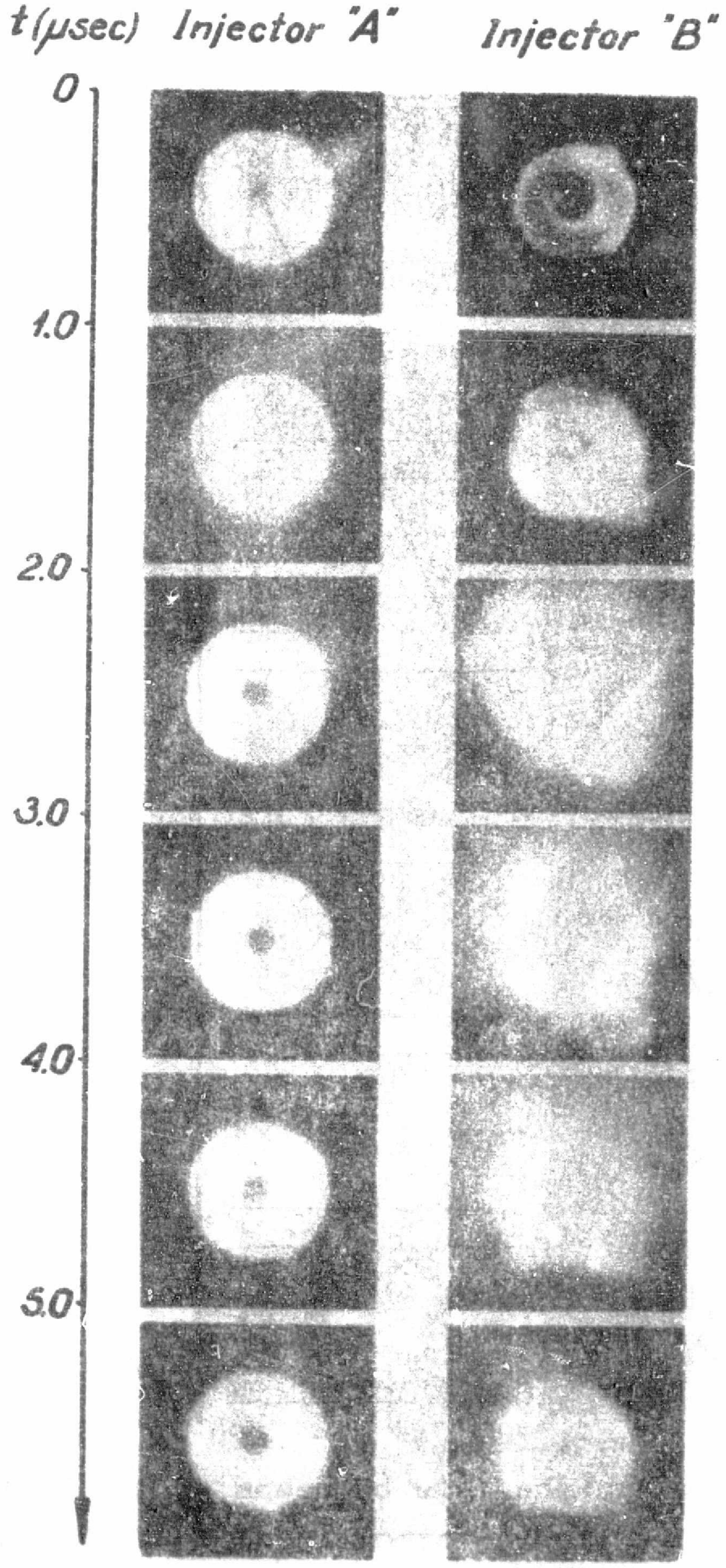

Fig.8. Plasma photographs made by means of the high-speed camera situated in front of the injector nozzles. Discharge parameters: U_0 = -20 kV, working gas - air, 0.5 cu.cm, τ = 350 μsec.

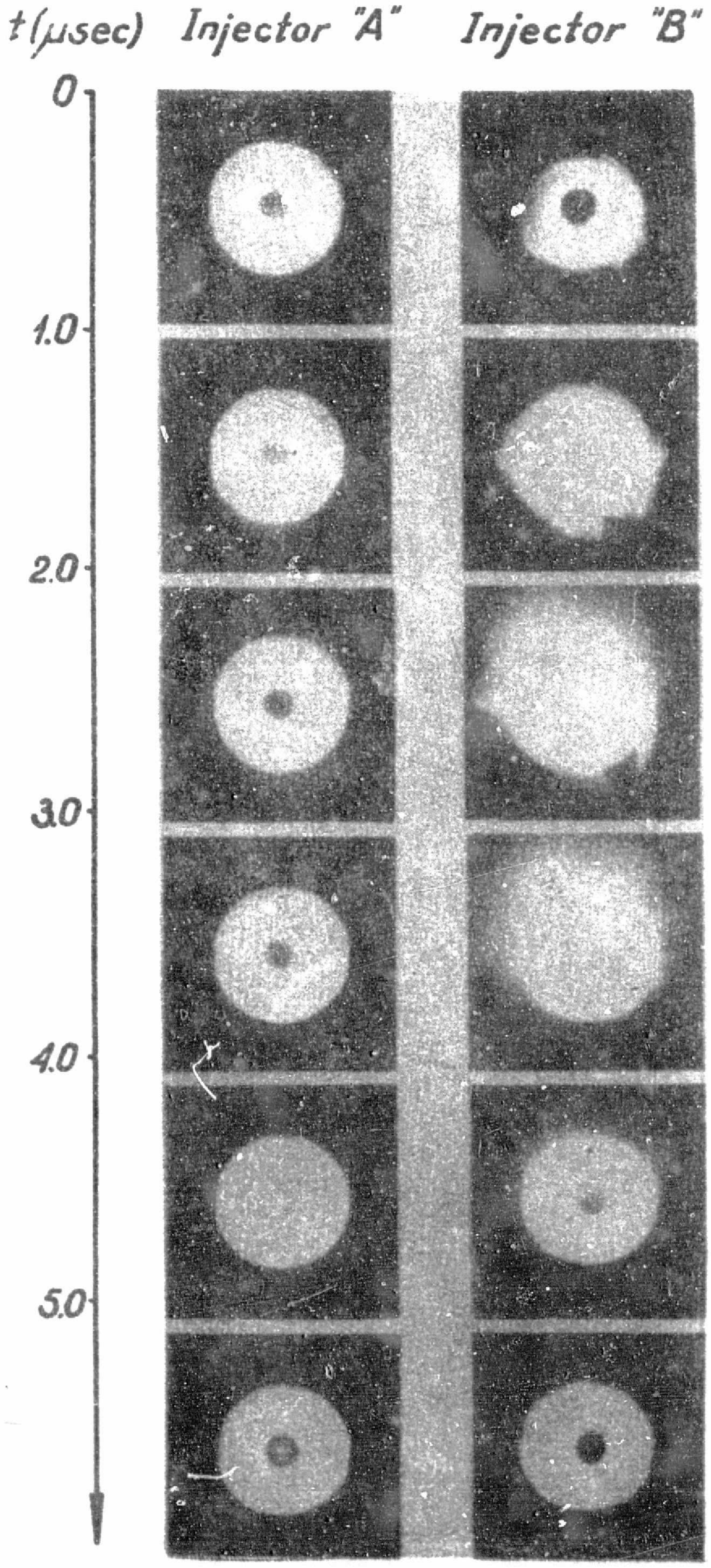

Fig.9. Plasma photographs made by means of the high-speed camera situated in front of the injector nozzles. Discharge parameters: U_0 = -20 kV, working gas - air, 1.0 cu.cm, τ = 350 μsec.