Abstract. **The possibility of using a long laser spark for protecting objects against lightning is studied. Conditions under which the electric charges from clouds can be guided reproducibly along a long laser spark are found. Experiments reveal that the interaction between the laser spark and the discharge from an electrode rod (lightning rod) leads to a decrease in the lifetime of the streamer corona burst, as well as to an increase in the current of the developing leader and its velocity compared to the case without the laser spark.**

Keywords: *laser spark, protection against lightning, laser application.*

1. Introduction

The problem of protection of terrestrial objects against lightning has not been solved satisfactorily so far. Lightning strikes on industrial objects like petrochemical complexes, nuclear power plants, ultrahigh voltage transmission lines and substations, rocket-launching devices, etc., may turn out to be extremely hazardous. The electromagnetic pulse from a close-range strike of lightning also results in a breakdown of telecommunication equipment and its operation, computer networks, and control systems. Consequently, stringent requirements are imposed at present on lightning protection measures [1, 2]. The traditional lightning protection systems being used currently are not always in a position to ensure the desired level of efficiency. This stimulates the quest for new approaches to solve this problem.

Laser protection against lightning is one of the most prospective trends that are being developed actively at present [3, 4]. While using this approach, it is assumed that the lightning discharge channel being developed is guided towards the conventional rod of the metal lightning rod along the plasma channel formed as a result of the laser-induced breakdown of the atmosphere. This method is based on the concept of an 'active' lightning rod, when a laser beam can be used for 'triggering' and guiding a positive ascending leader from the tip of a lightning rod to a negatively charged thunderstorm cloud. It is expected that in contrast to the traditional approach, the use of laser spark will make it possible to control efficiently the very process of protection from lightning, ensure the selectivity of lightning capture, and provide safety of tall objects and large areas.

In most experimental works, the effect of the laser spark length on the process of discharge development was studied only in the gaps between electrodes [5, 6], and an attempt at striking a lightning in the field tests with the help of a long laser spark was made only in Refs [3, 7]. Two cases of simultaneous occurrence of a strike on the lightning rod and triggering of a laser were registered in [7], but the lightning channel did not coincide with the optical breakdown channel. On the other hand, it is known from the experiments on initiation of discharge in the gap between electrodes that a long laser spark completely determines the development of the leader channel and its position in space [5]. However, the conditions under which a long laser spark can initiate an ascending leader or trap a lightning strike are not clear, and the field tests of laser protection against lightning carried out in Refs [3, 7] could not provide an answer to these questions.

Since field experiments are quite complex and expensive, it seems expedient to continue laboratory-scale studies of lightning protection systems. However, such studies must be carried out under conditions of the most appropriate simulation of the actual thundestorm situation.

In this work, we investigate experimentally the interaction of a laser spark with discharges induced by an artificial cloud of charged aqueous aerosol. The results presented in this work were published partly in Ref. [8].

2. Experimental

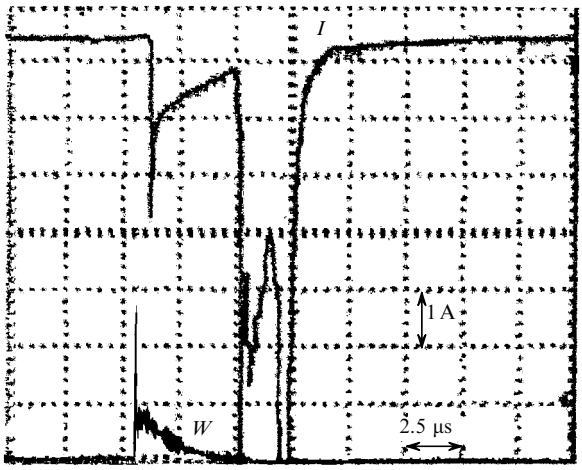

Figure 3. Oscillograms of the discharge current I in the presence of a laser spark (upper beam) and the shape of the laser pulse W (lower beam).

recorded. In this case, the duration of all discharge stages was much longer than on the oscillogram screen even in the case of capture.

If the laser spark was in the region A, no connection between its emergence and the formation and evolution of the discharge was observed for all the heights of the electrode rod in spite of a high electric field strength ($10-16$ kV cm^{-1}) in this region (a total of 20 laser shots was carried out for this purpose).

To determine the role of the laser spark in the evolution of the discharge, we carried out a series of experiments for studying the discharges in the gap between the CAC and the rod without the laser spark. Fig. 4 shows a typical oscillogram of the discharge current passing through the rod in this case. The oscillogram clearly shows all the stages of the discharge evolution, including the corona burst, leader stage and the main stage. However, the duration of these stages is much longer than in the case when a laser spark is present in the gap (see Fig. 3).

A comparison of the discharge characteristics in the gap between the CAC and the rod, obtained with/without a laser spark in the gap, and an analysis of the conditions of their evolution show that the laser spark formed at the tip of an earthed electrode does not facilitate the emergence of ascending leader discharges if the electric field of the cloud is weaker than that required for the development of a discharge in the absence of a spark. A fairly high probability of discharge channel capture by a laser spark is observed only for large values of the cloud charge, when the electric field of the CAC is in a position to initiate an ascending leader even in the absence of a spark. Consequently, the emergence of a leader with or without a laser spark occurs for close values of the external electric field produced by CAC. However, a long laser spark formed in the vicinity of an earthed electrode may accelerate the process of formation of a stable leader and its propagation towards the CAC.

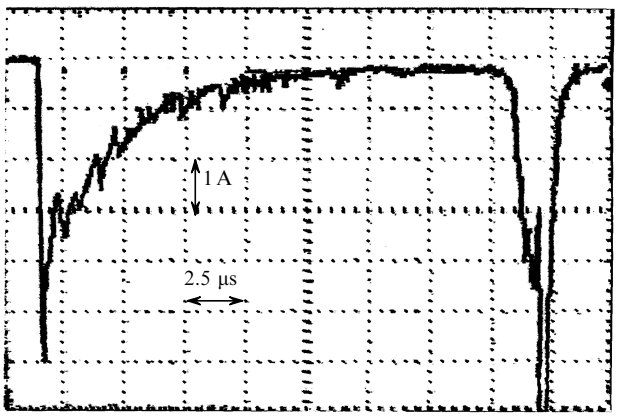

Figure 4. Oscillogram of the discharge current I in the absence of a laser spark.

Table 1 contains the results of processing of the current oscillograms for discharges 'captured' by the laser spark, as well as the discharges observed without a laser spark. It can be seen that the formation of a laser spark near the tip of the electrode rod leads to a manifold decrease in the duration T_{cor} of the streamer corona burst before its transformation into a leader discharge, while the maximum current I_{cor} of the streamer corona and the charge Q_{cor} transferred by it decrease by just about 30 %. On the whole, similar relations hold between the duration of the streamer corona burst and the transferred charge for discharges with and without a laser spark. It can be assumed that the presence of a laser spark near the tip of the rod in the streamer corona region accelerates the process of its transformation into the first leader segment.

The velocity of propagation of the leader increases by almost an order of magnitude under the influence of a laser spark, thus decreasing the duration T_{lead} of the leader stage of discharge from 13 to 1.25 μs. In turn, the average leader

Table 1. Leader discharge parameters with and without a laser spark in the gap

Measured parameters	Mean values of measured parameters and their spread	
	with a laser spark	without a laser spark
Duration T_{cor} of the streamer corona burst before the emergence of the leader/μs	2.37 1.22 – 5.88	7.2 4.2 – 11.2
Maximum streamer corona current I_{cor}/A	3.37 1.88 – 5.0	3.95 2.46 – 5.0
Charge Q_{cor} of the corona burst/μC	5.0 2.07 – 15.8	6.7 2.8 – 14.8
Mean leader current I_{lead}/A	1.52 0.93 – 3.07	0.11 0.08 – 0.15
Duration T_{lead} of the leader current stage/μs	1.25 0.68 – 2.07	13.0 5.6 – 22.9
Leader charge Q_{lead}/μC	1.8 0.84 – 3.68	1.68 0.4 – 2.6
Amplitude I_m of the main discharge current/A	5.0 4.4 – 5.4	4.9 4.2 – 5.3
Duration T_m of the main discharge stage/μs	1.05 0.75 – 1.61	3.4 2.23 – 6.25
Charge Q_n of the aerosol cloud neutralized at the main discharge stage/μC	3.64 2.38 – 6.05	5.76 2.49 – 8.21
Q_n/Q_{lead}	2.28 0.98 – 3.79	6.7 1.1 – 22.6

current in the presence of a laser spark is an order of magnitude higher than without the spark (more than 1.5 A on the average as against 0.11 A). As a result, the total charge of the leader is found to be almost identical in both cases.

Thus, a laser spark accelerates the propagation of a leader discharge if it traps the emerging leader. The laser spark may increase the average velocity of the leader manifold. This is in accord with the results obtained in Refs [5, 6] according to which the presence of a long laser spark in the discharge gap increases the velocity of propagation of the leader by more than an order of magnitude in comparison with its velocity in the unperturbed gap. It is significant that the gap is covered the more rapidly, the larger the segment of the laser spark coinciding with the leader channel.

This effect is manifested clearly in our experiments also upon an increase in the length of the discharge gap between the CAC and the rod due to a decrease in the height of the rod (from 58 to 29 cm) on the earthed surface. In spite of the development of the ascending leader over the laser spark region, this led to an increase in the average time T_{lead} of its propagation from 1.25 to 5.7 μs, since the total length of the gap increases and the part covered by the laser spark decreases.

The parameters of the main discharge also differ significantly in the presence of a spark in the gap and without it. Although the current amplitudes of the main discharge in both cases are 4–5 A (see Table 1), the duration T_m of the main discharge stage and the charge Q_n neutralised in this time decrease to less than half as a result of 'capture' of the discharge. In both cases, a nearly identical growth of the main stage duration T_m is observed upon an increase in the time T_{lead} of propagation of the leader (Fig. 5).

In spite of the similarity in the increase in T_m and the increase in T_{lead}, the dependences of the charge Q_n neutralised at the main discharge stage on the leader charge Q_{lead} are of different types for charges with a spark and without it. In the absence of a spark, a tendency towards a decrease in the value of Q_n upon an increase in the leader charge Q_{lead} is manifested clearly. On the contrary, a weak increase in the value of Q_n upon an increase in the leader charge Q_{lead} is observed in the presence of a spark. It must be noted that the fraction of the charge left by the leader in the total charge neutralised at the main discharge stage (Q_n/Q_{lead}) is much smaller for discharges without a laser spark in the gap than in the presence of the spark (on the average, $Q_n/Q_{lead} \approx 6.7$ in the presence of the spark and 2.28 without it), especially for small values of the leader charge. For higher leader charges, only the charge left by the preceding leader is virtually neutralised under all conditions at the main discharge stage; i.e., $Q_n/Q_{lead} \to 1$.

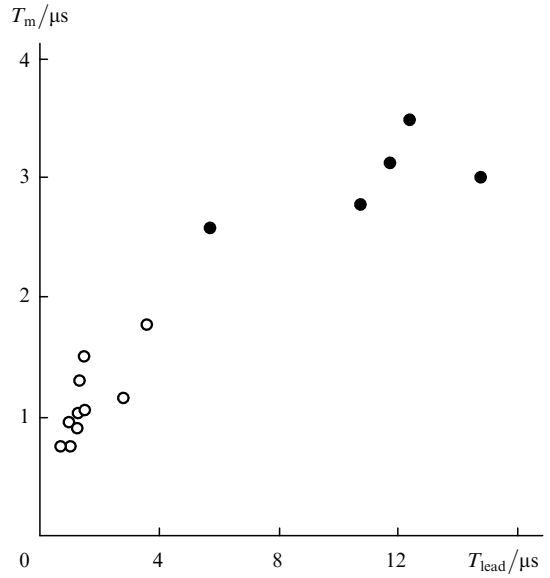

Figure 5. Duration T_m of the main discharge stage as a function of the duration T_{lead} of the leader current in the presence (○) and absence (●) of a laser spark.

4. Conclusions

Our experimental studies have shown that, in spite of its discontinuous structure, a long laser spark created in the vicinity of an earthed electrode may capture the channel of leader discharge developing in the gap between the electrode and a CAC. The capture takes place for a quite high electric field strength at the electrode, its value being close to that of the field required for the emergence of an ascending positive leader in the absence of a laser spark in the gap.

The creation of a laser spark near the tip of an earthed electrode allows a considerable decrease in the time of formation of a stable leader which starts propagating towards the cloud and captures a part of the laser spark. As a result, its velocity increases compared to the case when the discharge develops in the absence of a laser spark in the gap. This circumstance is of fundamental importance for laser systems of lightning protection. Indeed, owing to its interaction with the laser spark, the leader discharge developing from the tip of the lightning rod may well precede the ascending discharges from the object being protected during its advance towards an approaching descending leader, capture the latter and thus protect the object.

Acknowledgements. This work was supported by the International Science and Technology Centre (Grant No. 880-99).

References

1. International Electrotechnical Commission Standard: IEC 1024-1 (1990). Protection of Structures Against Lightning. Part 1: General Principals.
2. International Electrotechnical Commission Standard: IEC 1312-1 (1994). Protection Against Lightning Electromagnetic Impulse (LEMP). Part 1: General Principals.
3. Yamanaka T., Uchida S., Shimada Y., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **3343**, 281 (1998).
4. Ba el an E.M., Rai er Yu.P. *Usp. Fiz. Nauk*, **170**, 753 (2000).
5. Vasil ak L.M. *Materialy konferentsii po fizike nizkotemperaturnoi plazmy FNTP-98* (Proceedings of the Conference on Low-Temperature Plasma Physics) (Petrozavodsk, 1998) Part 2, p. 135.
6. Vasil ak L.M, Vetchinin S.P., Pol ako D.N. *Elektrichestvo*, **1**, 59 (1991).
7. Uchida S., Shimura E., Yasuda H., et al. *Opt. Zh.*, **66** (3), 36 (1999).

8. Apollono V.V., Firso K.N., Gerasimo D.N., Gla ko V.V., Konono I.G., Orlo A.V., Pol ako D.N., Sinke ich O.A., Sokolo a M.V., Temniko A.G., Vasil ak L.M., Vereschagin I.P. *Proc. XXV Intern. Conf. Phenomena in Ionized Gases* (Nagoya, Japan, 2001) Vol. 4, p. 65.
9. Vereschagin I.P., Antsupo K.V., Ba utkin V.V., Beloglo sk A.A., Makalsk L.M., Nikitin O.A., S soe V.S., Temniko A.G. *Proc. XXI Intern. Conf. on Lightning Protection* (Berlin, Germany, 1992) p. 25.
10. Apollono V.V., Baitsur G.G., Ermachenco A.V., Firso K.N., Konono I.G., Kone V.M., Ko alchuk O.B., Kralin V.V., Minenko V.R., Prokhoro A.M., Semeno S.K., Shubin B.G., Yamschiko V.A. *J. Opt. Soc. Am. B*, **8**, № 2, 220 (1991).
11. Temniko A.G., Orlo A.V. *Elektrichestvo*, **8**, 18 (1996).
12. Vereschagin I.P., Temniko A.G., Koshele M.A., Makalsk L.M. *Proc. IX Intern. Symp. on High Voltage Engineering* (Graz, Austria, 1995) p. 2165.