ON LASER SPARK AIDED LIGHTNING PROTECTION

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Abstract – **In the last years, the laser spark, discovered in 1963, is investigated in interaction with a high-voltage gas discharge and intended to be applied for lightning protection of objects whose destruction is fraught with catastrophic consequences or high costs. One of recent advanced developments in active lightning protection is the use of optical breakdown of air by laser radiation for favorable safety orientation of lightning stroke. In the paper, relevant laboratory test results are summarized and a recent patent for active lightning protection device, with lightning energy extraction is described and analyzed in the light of some results of recently performed experimental studies. In particular, the detection, measuring and evaluation of the charge accumulated on the upper part of the grounded cylinder seems to be more realistic than the electric field intensity monitoring in bottom layer of thunder clouds.**

Keywords: laser spark, active lightning protection, high-voltage gas discharge, lightning energy extraction.

1. INTRODUCTION

The laser spark can be visually observed if a ruby or neodymium laser gigantic pulse beam with around 1 J energy and half amplitude duration of 30 ns is concentrated in a spot with radius of about 0.1 mm. This means a peak power of P = 33 MW. The efficient value of the electric field in the light wave results from Poynting vector to be more than 6 MV/cm:

$$S = E \times H = \frac{E^2}{z_0};\; z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \mu_0 c \approx 120\pi\ [\Omega]$$
$$E = \sqrt{z_0 S} \approx \frac{\sqrt{120P}}{r} = 19.41\sqrt{\frac{P}{\pi r^2}} \approx 6.3\ [\text{MV/cm}] \qquad (1)$$

This is approximately than 200 times more than the breakdown electric field in the case of DC electric field, which is about 30 kV/cm, the same as in the case of high and ultrahigh frequency fields.
Various laser types used for spark generation and their radiation wavelength are listed in the following table.

Tab. 1

Laser type	CO_2	Nd	Ti-Sapphire	Rb	KrF excimer
Plasma structure	discrete	discrete	cont	discrete	cont
λ [μm]	10.6	1.06	0.8	0.694	0.248

2. LABORATORY STUDIES

2.1. Experiment between metallic electrodes

In the years 1972-1976, on the external test stand of St. Petersburg Polytechnic University [5], using an optical quantum generator GOS-1001 laser and large focus distance optical system, a long high ionized channel was obtained with 2 GW laser beam (50 ns, 100 J). With an optical amplifier, having a multiplication coefficient 1.5 – 2, the maximal energy in the pulse was 160 J and the mean power 5 GW, with beam divergence less than 1′. With this installation a horizontal laser spark of 60 m length was obtained, composed from many brightly lit regions with the length of several cm. To direct vertically this laser spark two total internal reflection prisms was used. Because of beam energy absorption in the prisms only 1 m length vertical optical spark could be obtained, in which the high ionized plasma rest during about 25 μs. In case of a good synchronization of laser with the source of high voltage pulse generator, this time is enough for the accumulation in the spark channel of a spatial charge of opposite to the voltage pulse sign, as it happens in the case of classical metallic rod with the same dimensions.
If the corona inception electric field at laser light frequency is about E_i = 6 MV/cm, the largest radius of concentrated 5 GW laser beam should be less than:

$$r_m = \frac{\sqrt{120\,P}}{E_i} \approx 1\ [\text{mm}] \qquad (2)$$

The positive high voltage pulse of 2.7 MV and the front time 3.5 ms was applied to the 2 m diameter lattice sphere, disposed at 10 m above the ground. The tests were mate in two steps.
First the setup and the dimensions of the models of protected objects was selected for which the increasing of protective rod height with 1 m (largest length of vertical laser spark) is more efficient (largest difference between the probabilities of stroke to the protected object).
In the second step, the 3.8 m height of the lightning protection rod was increased by 1 m laser spark. The laser was activated when the leader induced charge on the protected object reached a known critical value. First time the test were made without laser spark,

afterward with laser spark and finally with a 4.8 m metallic rod.
The tests showed that the presence of the 1 m length laser spark decreases the probability of the stroke to protected object from 0.26 to 0.08, i. e. three times. Similar result (p = 0.12) was obtained with the 4.8 m metallic rod.
Tab. 2

		Number of discharges			
Rod height, m	Number of tests	To object	To rod	To earth	Probability of object damage
3.8	307	79	102	126	0.26
4.8	125	15	57	53	0.12
3.8+spark	50	4	21	25	0.08

The tests confirm the possibility to (partially) replace the lightning protection rod with a laser spark and use it for lightning stroke orientation.

2.2. Experiment between metallic electrode and charged artificial aerosol cloud

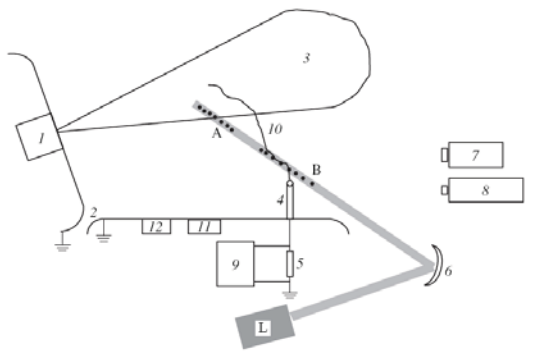

Fig. 1: Experience setup [4]

1. Aqueous negative charged aerosol generator, exit nozzle 6 mm diamater
2. Grounded metallic plane
3. Cloud of charged aerosol
4. 100-580 mm rod with spherical or conic top
5. Low inductivity shunt 4 or 10 Ω
6. Spherical mirror
7. Digital camera
8. Video camera
9. Tektronix TDS 220 oscilloscope
10. Channel discharge
11. String sensor for electric field
12. Dynamic antenna for cloud charge monitoring wit S8-17 storage oscilloscope

The interaction between laser spark and the lightening discharge is analyzed in [4].
The experimental investigation demonstrated that an extended (0.3 – 0.5 m) laser-induced spark, having a discrete structure, initiated in the vicinity of a grounded rod may intercept the channel of a leader discharge, arising from the grounded electrode toward an artificially highly charged aerosol cloud. The interception occurs when the electric field intensity near the electrode is close to the value required for the emergence of an upward positive leader.
When the laser-induced spark was developed in position A, no correlation was observed between the spark and the emergence or development of an upward discharge from the grounded electrode (for electric field intensity from 16 to 20 kV/cm). When the spark was developed in the vicinity of grounded electrode top (position B), a correlation was revealed between the emergence of the spark and the development of the main discharge between the cloud and the rod (from electric fields ranging from 12 to 16 kV/cm). Only bottom part of the leader discharge was intercepted by the laser spark, while the plasma formation closest to the cloud was not involved in this process.
Several μs after optical breakdown, a flash of streamer corona was observed. In the following 2 – 4 μs this corona transforms in to leader which is followed by the 1 μs main discharge after 1 -3 μs.
The experiences presented in [4] as the previous results cited there, demonstrate that the presence in the region of a laser induced spark in the charged cloud-grounded electrode gap causes an acceleration of the leader discharge propagation. The leader charge in the presence of a spark was several times lower than in its absence, probably because that the spark heats the air in front of the leader and accelerate the decay of negative ions.

3. ACTIVE LIGHTNING PROTECTION WITH LIGHTNING ENERGY EXTRACTION DEVICE
Patent [7] description

In fig. 2 the setup of the proposed device is shown and its function is illustrated in fig. 3, where transparent arrows show the signal orientation and the black ones the direction of the energy.
As lightning divertor is used one vertical metallic cylinder (6) with a high permittivity dielectric thick glass (7) inside. The inside surface of dielectric glass is partially covered with earthed conducting layer 8 and the upper rest of the surface is ribbed to increase the flashover voltage. The cylindrical tube 6 is insulated from earth and connected to the upper end of the transformer T primary winding with earthed bottom end. The capacitance C between the cylindrical divertor 6 and the internal conducting coating 8 and the inductance of the transformer T primary winding form an LC oscillating tank. In the center of coated portion of the dielectric glass is a controlled moving diachronic mirror, whose normal to the reflecting surface form a free varying sharp angle with the axis of the glass. In front of the mirror at least two lasers with coaxial beams are fixed: one for extended optical spark, preferable working in

infrared range and the other one for atmosphere scanning, to detect critical charge density accumulation in clouds.

The axis of the reflected beams must be able to describe a circular upturned cone with the tip in the center of the mirror and tangent to the upper margin of the metallic cylinder 6, when appropriate position of the mirror is assured.

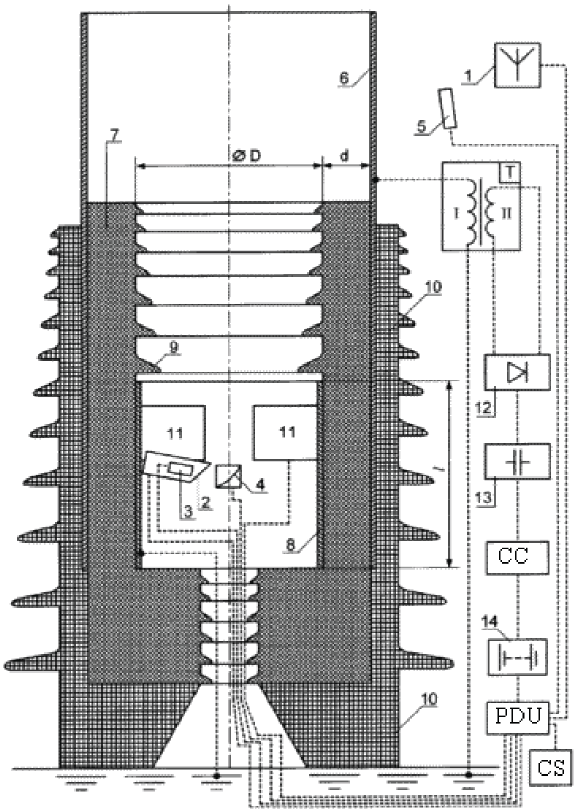

Fig. 2: Active lightning protection with lightning energy extraction device setup

1. System for static control of electric field intensity in air
2. Infrared pulse laser (Nd ~ 10^3 J e.g.) for long laser spark
3. CO_2 laser for atmosphere backlight and scanning
4. Diachronic mirror
5. Optical receiver
6. Grounded through transformer (T) primary winding metallic cylinder – lightning divertor
7. High permittivity dielectric glass
8. Grounded metallic coating
9. Internal ribbing to avoid the surface discharge
10. Insulator
11. Mirror protection air jet makers
12. – 14 Rectifier, current converter (CC), battery

PDU - Power and distribution unit, CS – control system

The secondary winding of the transformer T is connected to the rectifier 12 charging the condenser 13, which charges the accumulator 14 through the converter CC. The accumulator is feeding all the systems of the device.

The system 1, for the monitoring and detection of spatial charge accumulation, is running permanently and starts the device when the modulus of the electric field in at least two points of vertical path reaches any critical value.

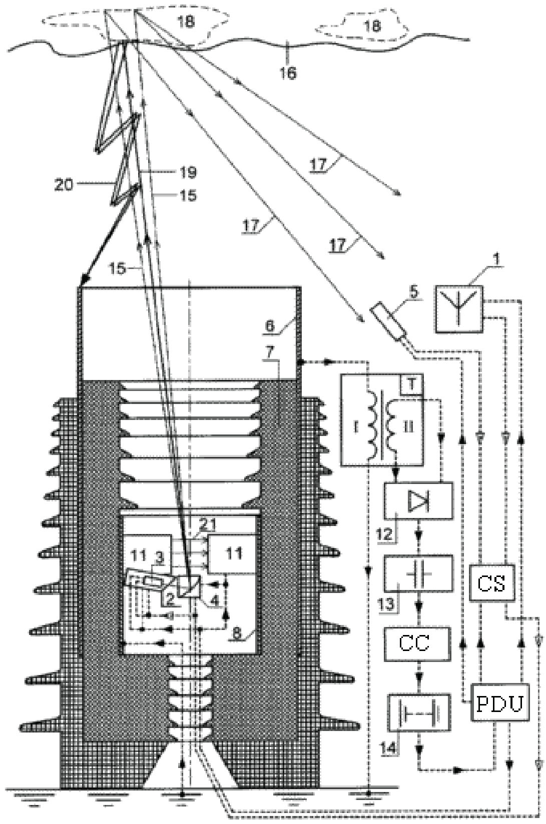

Fig. 3: Active lightning protection and lightning energy extraction device function

15 Probe laser 3 radiation beam
16 Bottom layer of thundery clouds
17 Reflected probe laser 3 radiation
18 Critical space charge density
19 Laser 2 radiation beam
20 Lightning channel
21 Mirror protection laminar air jet

When the modulus of electric field reaches the critical value, the system for static control of electric field intensity in air 1 send a start signal to the control system CS, which starts all the systems of device. As source for scanning the atmosphere can be used a CO_2 laser 3 with polarized beam. The beams of the two lasers 2 and 3 must be closed each to other and parallel. The laser 3 runs periodically all the time and the laser 2 emits a pulse only when the signal from CS is received. The beam 15 of laser 3, entering the through the bottom layer 16 of thunder clouds, is reflected by them and scattered. The moving mirror 4 directs the beam 15 to scan an enough large surface of the clouds in short time.

When the optical receiver 5 with polariscope detects a critical modification of the reflected beam polarization due to electric field it sends a signal to CS, which starts the laser 2 and stops the mirror for a short time, enough long for laser pulse generation. As a result, the pulse beam 19 is directed by the stopped mirror in the same direction, when the strong electric field was detected (18). The optical spark generated by the beam 19 initiates a streamer followed by leader between the charge concentration and the top of the metallic tube 6. The surge current 20 follows the circuit: earth, metallic coating 8, metallic tube 6, leader channel, the cloud 16. This surge current produces damped oscillations in the LC tank formed by the capacitance *C* between the coating 8 and the metallic cylinder 6 and the inductance *L* of the primary winding of parallel connected transformer T. The induced in secondary winding of T voltage is rectified by the full-wave rectifier 12 and used to charge almost instantly the condenser 13. The accumulated in the condenser energy is converted by CC and used to charge the accumulator battery for PDU and others consumers feeding.

The capacitance *C* between the coating 8 and the metallic cylinder 6 can be easy evaluated as follows:

$$C \approx \frac{2\pi\varepsilon_0\,\varepsilon_r\,l}{\ln\dfrac{D+2d}{D}} \qquad (3)$$

All the dimensions are given in fig. 2.

4. CONCLUSIONS

1. The experiences show that the laser spark can replace a metallic rod for the orientation of lightning stroke and the use of this technique can reduce two and more times the probability of protected object damage.
2. Electric field intensity monitoring should be made not in bottom layer of thunder clouds as in [7], but in the vicinity of grounded electrode. This is simpler and more efficient.
3. The electric field near the top end of the protection electrode can be evaluated measuring the charge accumulated on the upper part of the grounded cylinder.

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