# Prebreakdown Processes and Electric Fields in Water with Screened Electrodes

S.M. Korobeynikov[1,2], D.V. Vagin[1]
[1]Novosibirsk State Technical University
[2]Lavrentiev Institute of Hydrodynamics SB RAS
Novosibirsk, Russia
korobeynikov@corp.nstu.ru

A.V. Melekhov
Institute of Laser Physics SB RAS
Novosibirsk, Russia

***Abstract*—Prebreakdown processes in water with modified electrodes were studied by optical and electrooptical methods. Nonelectrode and postbreakdown streamers are registered. Macroscopic and microscopic electric fields close to anode and cathode breakdown channel are measured. The conductivities of both streamers are estimated. Prebreakdown Kerr fringes in water were simulated by finite elements method. The comparison of simulation results with experimentally obtained data allows to estimate the macroscopic electric field and streamer conductivity. Macroscopic fields differ one from another: field close to cathode directed streamer has value 300 kV/cm, field close to anode directed streamer has value 2 MV/cm.**

***Keywords— Streamers; electrical strength; pulsed power; water; Kerr fringes; numerical simulation; finite elements method.***

## I. INTRODUCTION

Water as insulation medium is most suitable for pulsed power system due to high dielectric permittivity and high pulse electric strength. Power of pulse systems could be increased if electric field will be increased. Breakdown initiation on electrodes surface limits the pulse electric strength. That is why it was proposed to decrease electric field in the places of initiation with the help of special conductive layers close to electrodes [1,2]. These steps perform to increase the pulse electric strength of water insulation. Optical studies of breakdown and prebreakdown processes in case of screened electrodes were studied early.

The images of early stages of nonelectrode streamer in water are presented in the paper [3]. This kind of streamers sometimes appears in case of screened electrodes. Experimental setup and measurement technique are described early in [4, 5]. The experiments were performed with using voltage pulses with characteristic rise time $\tau_f \approx 0.6$ μs and amplitude U up to 200 kV. There were used spherical electrodes 35 mm in diameter and the gap between them was d = 3.5 mm usually. Deionized water with the specific conductivity $\sigma \approx 10^{-7}$ (Ohm·cm)$^{-1}$ went into the cell from water purifier closed loop. The registration of prebreakdown and breakdown processes was performed with the help of the shadow and Kerr methods by application a semiconductor laser with wavelength of $\lambda = 0.61$ μm and pulse duration at half-height of 3 ns. The photo registration was made with the digital camera with resolution of ≈ 10 μm in the mode of opened diaphragm. The electrooptical scheme of measurements was adjusted for minimum light transmission in the absence of the electric field. Therefore, the radiation of secondary ionization processes after the breakdown was also registered by the camera and it was superimposed on the image of the Kerr fringes.

Kerr effect is the really useful tool for prebreakdown process studies. Earlier, experimental Kerr fringes concerning prebreakdown charge emission and bubbling have been obtained in nitrobenzene [6], anode directed and non-electrode streamers in the water [3-5]. But experimental estimations of electric field have been made very approximately. The goal of the paper is a simulation of Kerr fringes for a case of streamers appearance in the water.

## II. EXPERIMENTAL RESULTS

Figure 1 shows the shadow photo of the nonelectrode streamer in the case of a screened anode creating increased electric conduction near the anode and a lot of anode directed streamers initiated on cathode. The point of the initiation of a characteristic single nonelectrode streamer propagating simultaneously to the anode and cathode in the form of “half_streamers” is seen at the distance δA ≈ 1 mm from its surface. Cathode directed “half streamer” has supersonic velocity and anode directed one has subsonic velocity.

Fig. 1. Shadow photo (a): top, modified anode; bottom, metallic cathode; U =142 kV, d = 3 mm, t = 2.05 μs; dark points are microparticles; (b) enlarged part of the interelectrode gap with the nonelectrode streamer.

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Figure 2 demonstrates the final stage of breakdown, initiated by nonelectrode streamer. Here the breakdown channel luminescence is overlaid by Kerr picture. One could see that before breakdown initiation the electric field is increased in the centre of the gap. It's maximal value is 510 kV/cm. The direction of tree branches shows that breakdown channel develops both to cathode and anode. To all appearances the first prebreakdown event is supersonic "half-streamer" to the cathode [3]. When discharge channel touches the cathode surface the potential of the cathode should be transferred to the subsonic half-streamer branches. Then this halfstreamer should reorganize into supersonic streamer developed into anode direction. For the proof of this picture it is important to estimate the channel conductivity.

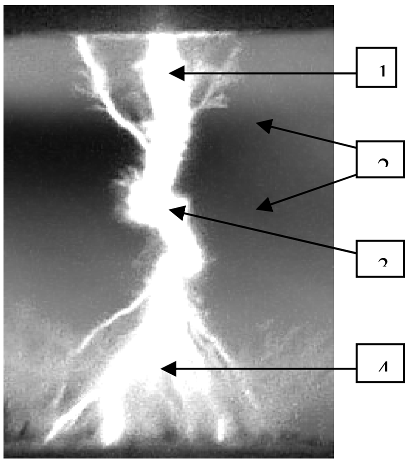



Fig. 2. Discharge channel in case of screened electrodes. Kerrogram and inherent glow of discharge. Voltage U= 145 kV, gap d= 4 mm. Kerr picture was obtained at tl = 1.45 µsec, breakdown occurred at tb = 1.7 µsec. 1 – anode streamer, 2 - Kerr darkening, 3- the place of breakdown origin, 4 - cathode streamer.

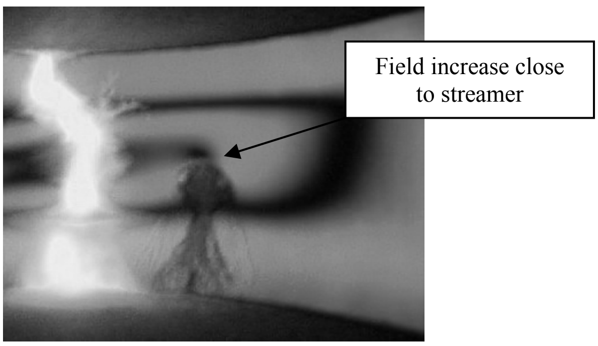


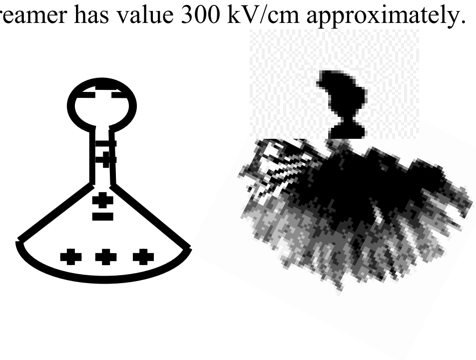

Fig. 3. Kerrogram and inherent glow of discharge. Voltage U= 132 kV, gap d= 3.5 mm. The moments of Kerr picture and breakdown were the same tl ≈ tb = 1.4 µsec. Electric field strength at the centre of the gap E ≈ 720 kV/cm.

The kerrogram that perform to estimate cathode streamer conductivity is presented in Fig.3. Here it is several branches of cathode directed half-streamer that reach the cathode.

## III. Discussion

The electric field close to the tips of halfstreamers could be estimated if suppose streamers schematically (Fig.4).

The anode directed streamer with the characteristic size $R_a$ has a smaller surface than the cathode directed streamer with the size $R_c$. For the anode directed streamer $S_a \approx 2\pi$ (hemisphere), for the cathode directed streamer $S_k \approx (\pi/2)$ (the cone with the angle $\approx\pi/2$). At $R_a \approx 50$ µm and $R_c \approx 250$ µm the macroscopic field strength of the anode directed streamer $E_{ma}$ is six times higher than that in front of the fan of the cathode_directed streamers $E_{mc}$. The estimations [7] give the value of **microscopic** field close to the tips both of anode and cathode halfstreamers approximately 10 MV/cm, while **macroscopic** fields differs one from other: field close to cathode directed streamer has value 2 MV/cm, field close to anode directed streamer has value 300 kV/cm approximately.



(a) (b)

Fig. 4. Principle scheme of the nonelectrode streamer (a) and superposition of fragments of the cathode and anode 2 streamers (b) [4] at E ≈ 800 kV/cm, t = 1.0 µs.

The Fig. 3 perform to estimate the conductivity of streamers. One could see the electric field close to anode directed halfstreamer has increased value. This conclusion could be done due to marginal changes in the intensity of Kerr fringes. According to expression [4]

$$I/I_0 = \sin^2(\pi B_k \int E_\perp^2 dx) \qquad (1)$$

marginal changes in the intensity mean marginal changes in the phase in the expression (1). Here $B_k$ is the Kerr constant ($B_k = 2{,}6\cdot 10^{-12}$ cm/B$^2$ ), $E_\perp$ is the electric field component that is perpendicular to laser beam direction, x is the probing beam direction.

This peculiarity performs us to estimate the conductivity of anode streamer channel. If suppose that channel has high conductivity then the cathode directed part of the streamer will have the potential of cathode. Phase shift due to field increase close to nearly spherical anode directed part of the streamer could be estimated in supposition of spherical symmetry. It is simply to obtain that phase shift

$$\Delta\varphi \approx \pi\ B_k \cdot (3\pi E_0^2 r_0/8) \qquad (2)$$

where $E_0$ – electric field close to anode directed streamer, $r_0$ – radius of streamer zone. In case of high conductivity $E_0 \approx U/r_0$ and phase shift $\Delta\varphi$ should be equal $\pi$ approximately.

Really phase shift is small enough $\Delta\varphi_{real} << \pi/2$. Taking into account both the change of intensity of Kerr fringe close to the streamer and the width ratio of dark and light Kerr fringes one could estimate $\Delta\varphi_{real} \approx (\pi/4 \div \pi/8)$. That is why the potential of anode directed half-streamer is two or three times less than U. What does it means? It means that conductivity of cathode directed streamer is low and the streamer tip doesn't have electrode potential. In comparison anode directed streamer according analysis of experimental data [5] has high conductivity and streamer tips have electrode potential approximately.

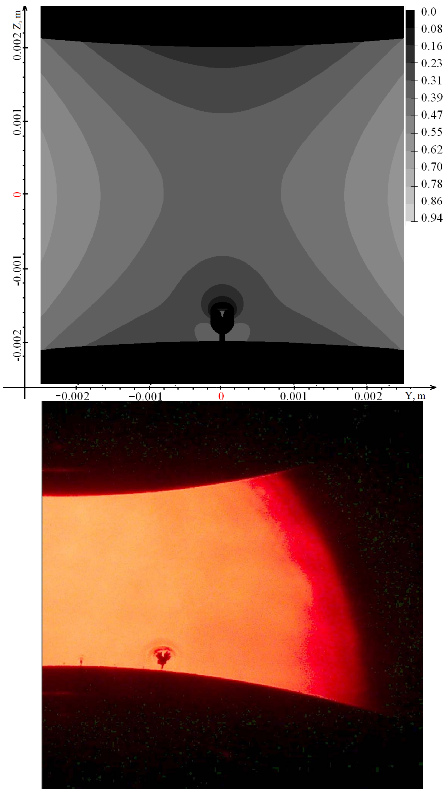



Fig. 5. Numerical simulation result of the relative light intensity distribution in comparison with experimental data [3] for "small" streamer on cathode.

Fig. 5, 6 show the results of numerical modeling of the relative light intensity distribution for two models with different shape and size of the streamer in comparison with experimental results.

For both models the voltage amplitude between the electrodes was 180 kV. The radius of both hemispherical electrodes was 25 mm, the distance between them – 4 mm In both case streamer has been formed corresponding to the previous experimental results [2, 3] and has touched the cathode. In the first case head radius of streamer has been 0.45 mm, base length – 0.2 mm, and his dielectric properties have been close to the perfect conductor.

On Figure 5 the first image corresponds to simulation with non-electrode streamer assuming that it has high conductivity.

Figure 7 shows the graphs for electric field module values over the interval from the streamer head to the anode for models with high-conductive "small" streamer (a) and with high-conductive "big" streamer (b).

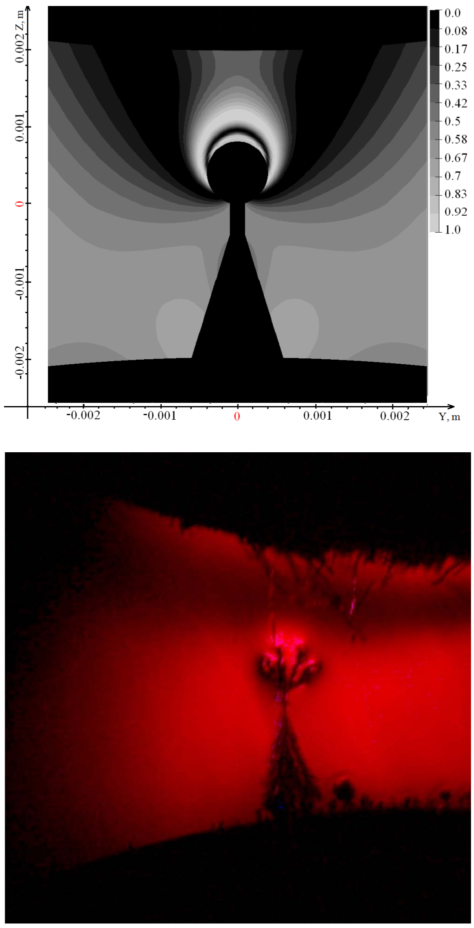



Fig. 6. Computed distribution (case of conductive streamer body) in comparison with experimental record for "big" non-electrode streamer at the moment of cathode contact.

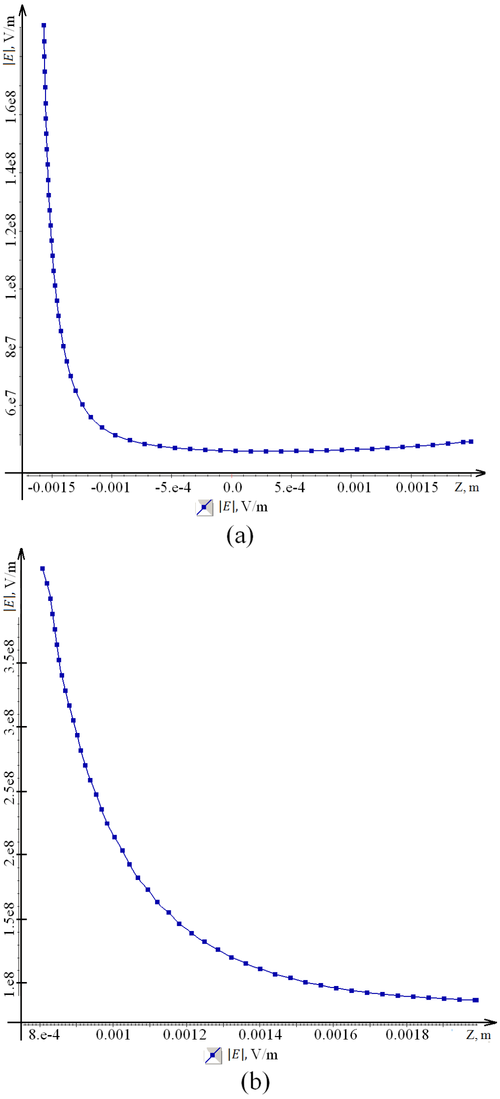



Fig. 7. Graphs for electric field module values over the interval for model with "small" cathode streamer (a) and with "big" nonelectrode streamer (b).

The comparison of simulated Kerr picture with experimental one allows us to point out the following conclusions. The computed and experimental pictures of small cathode streamers are practically identical. If we take into account that in computations the streamer surface has been considered as equipotential surface, then the coincidence means high conductivity of the streamer. Moreover, computations give us more realistic estimations of the electric field near streamer. Our previous estimations have given values in case of anode directed small streamer of 2 MV/cm approximately. Now, more realistic estimation is 2.3 MV/cm. In case of nonelectrode streamer the situation is more complex. The computed phase shift (Fig.3) close to the streamer head is $\sim 5\pi/2$, whereas experimental one is $\sim \pi/2$. This discrepancy shows that charge redistribution in streamer body has not taken place. Therefore nonelectrode streamer has low conductivity.

## IV. Conclusion

In case of screened electrodes nonelectrode streamers appearance takes place. Anode directed half streamer has subsonic velocity and high conductivity. Cathode directed half streamer has supersonic velocity and low conductivity. Microscopic field close to the tips both of anode and cathode halfstreamers is approximately 10 MV/cm, while macroscopic fields differs one from other: field close to cathode directed streamer has value 2 MV/cm, field close to anode directed streamer has value 300 kV/cm approximately.

Comparison of computed Kerr fringes with experimental one performs us to estimate electric field close to anode directed streamer. This value is 2 MV/cm. As for as non-electrode streamers, Kerr fringes close to small streamers are the same as these one far from streamer. The low sensitivity of this method didn't give possibility to estimate electric field strength. Big non-electrode streamer haven't high conductivity and electric field close to anode directed head was estimated as 300 kV/cm approximately.

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