Nonelectrode and Postbreakdown Ionization Processes in Water

Sergey Mironovich Korobeynikov, Alexandr Victorovich Melekhov, and Vitaly Georgievich Posukh

***Abstract*— Space charges that determine spatial distribution and magnitude of local electric fields play an important role in different fields of science. Here, we show the results of optical and electro-optical studies of nonelectrode and postbreakdown ionization processes in near-electrode space charge layers inside water. The nonelectrode streamers develop in the form of cathode and anode semistreamers initiated at the same point. Postbreakdown streamers are registered near the main breakdown channel. The second type of postbreakdown streamers is initiated at the cathode. Both streamers are spread through the nearly whole negative space charge region.**

***Index Terms*— Electrical strength, pulsed power, streamers, water.**

I. Introduction

PULSE electrical strength of water is very important for design of pulsed power system, z-pinch accelerators with water pulse forming lines especially [1]. There were several attempts to increase the breakdown strength of water. First, successful experiments were fulfilled with so called diffusion electrodes [2]. The electrical strength after forming of semiconducting layers close to electrodes increased by 3/4 times in comparison with pulse electrical strength of deionized water. These layers were produced by forcing of electrolyte through porous electrodes. In spite of outstanding result, this technology did not find application in pulsed power technique. The main reason was that layers could not keep their configuration due to diffusion, buoyancy, and electric forces.

The second significant result was obtained with glycerol as dielectric media [3]. The conductive layers in glycerol were prepared by pulse heating of electrodes. Electrical strength of the gap was increased significantly comparing with the strength of gap without layers. Unfortunately, this technology was not used in water pulse systems due to technological problems of pulse heating of large electrode surfaces.

Our attempt of water pulse breakdown strength increase is based on electrode modification with the help of ion-exchange membranes. Previous electro-optical measurements [4] display that modified electrodes make it possible to enhance local field strength 2/3 times more than the average field strength. Here is the space charge formed near the electrodes. In the gap after the breakdown, the field created by space charges remains during the relaxation time $t < \tau_m \approx \varepsilon \cdot \varepsilon_0/\sigma$, where σ is layer conductivity, $\varepsilon-$ is water permittivity. The breakdown of the gap with conductive layers has differences relative to breakdown with bare electrodes.

The goal of this paper is to register nonelectrode and postbreakdown phenomena specified by the redistribution of electrical field by space charges.

Manuscript received February 14, 2013; revised May 18, 2013 and November 22, 2013; accepted February 11, 2014. Date of publication March 18, 2014; date of current version April 8, 2014. This work was supported by Sibel Ltd.

S. M. Korobeynikov is with Novosibirsk State Technical University, Novosibirsk 630092, Russia (e-mail: kor_ser_mir@ngs.ru).

A. V. Melekhov and V. G. Posukh are with the Institute of Laser Physics, SB of RAS, Novosibirsk 630090, Russia (e-mail: melekhov@ngs.ru; vposukh@mail.ru).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2014.2307894

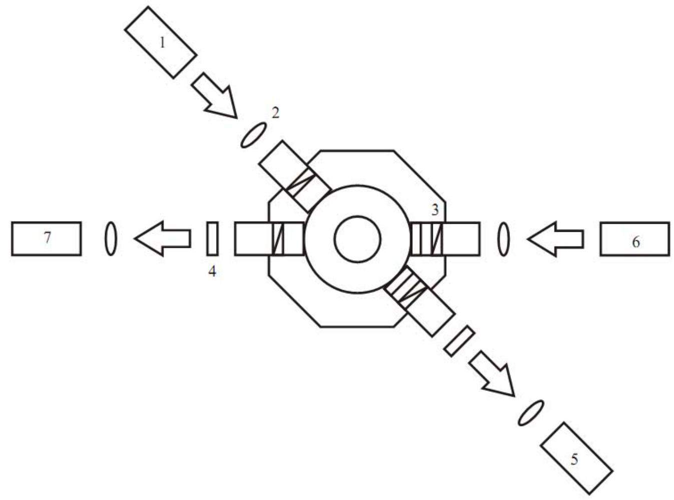


Fig. 1. Experimental setup. 1: He–Ne laser. 2: lens. 3: polarizer. 4: filter. 5: photomultiplier. 6: pulse laser. 7: photocamera.

II. Experimental Setup

The experiments were performed using voltage pulses with characteristics: rise time $\tau_f \approx 0.6$ μs and amplitude U up to 200 kV. Experimental setup is in Fig. 1. Here, spherical electrodes 35 mm in diameter were used and the gap d between them was from 3 to 4 mm. The electrodes are made of stainless steel and covered by special layers (Fig. 2). The cell was inserted into a water purifier closed loop. This was done to get deionized water inside the cell with the specific conductivity $\sigma \approx 10^{-7}$ $(\Omega \cdot \mathrm{cm})^{-1}$. The registration of postbreakdown processes was performed by the shadow method using a semiconductor laser with wavelength of $\lambda = 0.61$ μm, energy of 10–20 mJ, and pulse duration at half-height of 3 ns. The photo registration was made by the digital camera with

Fig. 2. Modified electrode. Dark spots show tracks of four previous discharges.

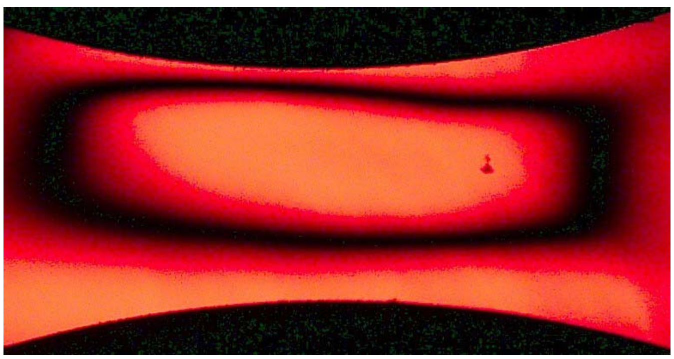


Fig. 3. Electro-optical map of interelectrode gap. The small nonelectrode streamer is more to the right of the center.

resolution of $\approx$10 μm in the mode of opened diaphragm as it was shown earlier [5], [6]. In some experiments, electro-optical method of prebreakdown electric field registration was used [4], [7].

Triangle voltage pulses with rise time $\approx$1–2 μs and decay time $\approx$0.1–0.2 μs were formed. High-voltage test cell is in the form of octagonal stainless steel box with optical windows. Deionized water with specific resistance of $\approx$10 M$\Omega \cdot$cm goes into the cell from the water purifier closed circuit.

III. Results

Optical pictures of nonelectrode streamers were presented earlier [6]. Here is shown an electro-optical picture (kerrogram) of nonelectrode streamer only (Fig. 3). Analysis of Kerr fringes shows that the electric field strength is nonuniform, its value in the middle part of the gap is two times more than the same near electrodes. The nonelectrode streamer initiates in the region of maximal electric field.

The postbreakdown streamers were registered more often than the nonelectrode ones. Fig. 4(a) shows the negative of kerrogram registered $\approx$50 ns before the breakdown (t_b is breakdown time, t_l is the time of laser exposition). A light closed oval corresponds to the average field strength $E \approx 510$ kV/cm along the beam path, the field strength in the central part is $E \approx 620$ kV/cm, and the average field strength in the gap is $E = U/d \approx 530$ kV/cm. The electro-optical scheme of measurements was adjusted for minimum light transmission when the electric field is absent. 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. Luminous branches near the cathode propagate generally in the radial direction from the discharge channel. The length of branches from the center of the discharge channel reaches 5 mm and their thickness is $\leq$0.1 mm. They are situated in the region of the enhanced field gradient.

To evaluate the velocity of radial discharge propagation, the shadow method was used. Fig. 4(b) shows a typical photo of postbreakdown processes. The analysis of such photos showed that with allowance both time delays between the moments of breakdown and laser pulse and the size of the shock wave zone from the discharge, the velocity of radial propagation of the discharge exceeds the sound speed considerably and equals $\approx$10 km/s.

The other type of postbreakdown streamers is shown in Fig. 5. The moment of laser pulse is before breakdown and that is why in the picture one can see of both Kerr fringes and luminescence of breakdown channel and postbreakdown streamers. Some of these streamers were initiated on the electrode.

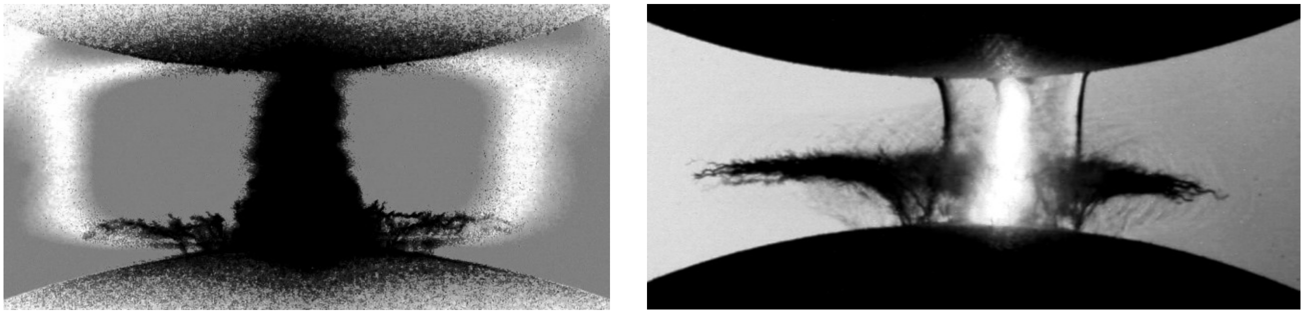
Another event was observed in case when a conductive layer is formed near the anode only. Fig. 6 shows the fragment of optical density perturbation from the anode where the cathode is a metal sphere ($U = 131$ kV, $d = 3$ mm, $t_b = 1.7$ μs, $t_l = 2.15$ μs). This perturbation moves from the anode with sound velocity.

IV. Discussion

Before the breakdown, conductive layers [2]–[4] and space charges close to electrode [7], [8] reduce the electrical field strength near the surface of electrodes and enhance it inside the gap that causes increasing pulse electric strength of liquids in large interelectrode gaps. Near the cathode a negative charge is formed and near the anode a positive one is formed.

After an instantaneous short circuit of interelectrode gap, due to a breakdown, the layer charge remains the same during the time τ_m and the distribution of electric field strength in the gap does not vanish. In Fig. 7, the qualitative distribution of dimensionless electric field strength E_z (a, b) and potential (c) near the electrode before and after the breakdown is presented. The distance z is measured from the electrode surface into the gap's depth. The region not directly adjacent to the discharge channel is considered here.

After the main breakdown, the potential reaches the maximum at the boundary of layer 1. Its value depends on the relation of sizes of near-electrode regions occupied by the space charge l and the size of the average gap region where the space charge was absent. For our conditions, the potential can be evaluated as $\varphi \approx (U \times l)/2d$. Z component of electric field could be significant near the electrode and exceed the average field before breakdown. Clearly, postbreakdown streamers shown on Fig. 5 arise due to this factor.



(a) (b)

Fig. 4. (a) Negative of prebreakdown kerrogram ($U = 214$ kV, $d = 4$ mm, $t_b = 1.4$ μs, $t_l = 1.35$ μs). (b) Shadow photo of afterbreakdown phenomena ($U = 108$ kV, $d = 3$ mm, $t_b = 1.0$ μs, $t_l = 1.65$ μs). The upper electrode is anode.

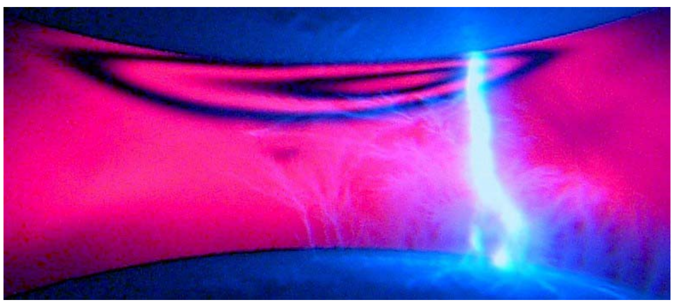


Fig. 5. Joint exposition of electro-optical picture (Kerr fringes) and discharge glow of breakdown channel and postbreakdown streamers.

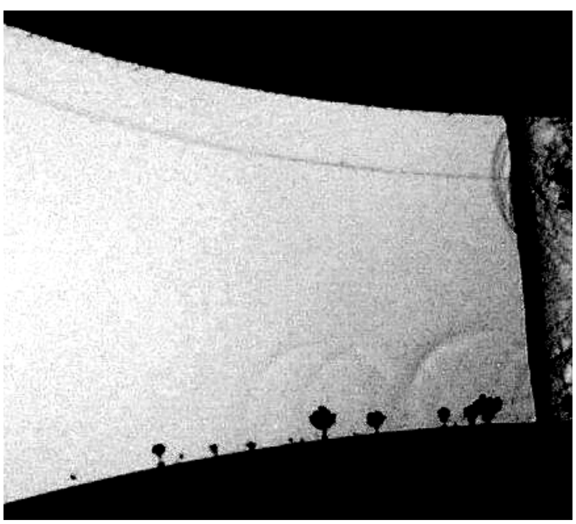


Fig. 6. Sound wave near the anode (upper electrode).

But more interesting is the radial electric field emergence near the breakdown channel especially. Then, the evaluation of the radial electrical field strength E_r from the discharge channel with the radius r can be roughly calculated by the next expression

$$E_r \approx \varphi/kr \approx (U \cdot l)/2rkd \approx (U/d)(l/2r)/k$$

where k is the coefficient of order 1. It follows from evaluations that at the contact point of space charge and discharge channel (a thin well-conducting cylinder), a transverse strength reaches a maximal value. For $U/d \approx 500$ kV/cm and $l \approx 0.1$ cm, the potential with respect to the electrode

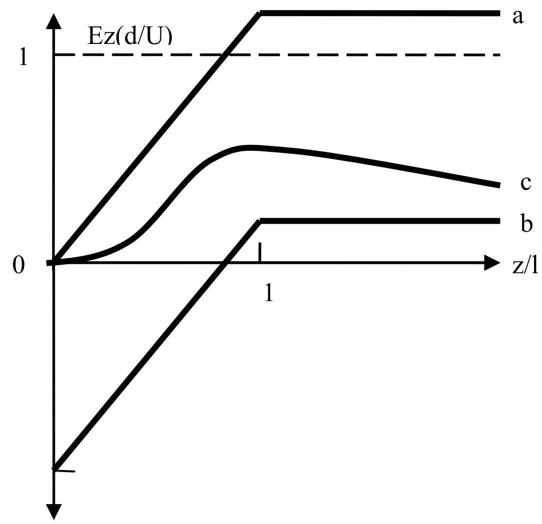


Fig. 7. (a) Before the breakdown. (b) and (c) After the breakdown (not close to breakdown channel).

is $\sim$25 kV. The radial field strength for a conductive channel with the radius $r \approx 0.05$ mm is estimated by several megavolts per cm, i.e., exceeds the prebreakdown strength of the field U/d. It should initiate the appearance of radial discharges near both electrodes. Moving along the charged layer, the discharge will neutralize the charge; a strong field zone will move farther and farther from the center. One could say that a transverse discharge should be propagated over the whole zone where the space charge is present. As a result of the polarity effect in strong nonuniform fields afterdischarge discharge is more probable to be near the cathode where the discharge channel becomes a temporary anode. In this case, the discharge propagates with supersonic speed. Near the anode, the channel is a temporary cathode; its speed is subsonic and it is not seen against the background of the shock wave of primary breakdown origin.

For conductive layers of size less than primary discharge channel diameter, the strength of transverse field is small and transverse discharges have lower probability.

It can be seen from Fig. 7 that after the breakdown the electrical field strength on the surfaces of electrodes reaches the value $E \approx U/d$ instantly and decreases toward the gap's depth. The results both to the gradient of electrostrictive pressure $P_E \sim -\varepsilon \cdot \varepsilon_0 \cdot E^2/2$ and the appearance of the Coulomb force acting on the space charge and liquid, correspondingly. Both these forces are directed to the electrode and due to them the liquid moves to the electrode that causes the appearance of an unloading wave moving from the electrode with sound speed. Indeed, sound perturbations near the anode were registered by using the shadow method (Fig. 6).

It looks like the electrostrictive waves in nonuniform fields at pulse voltage that were considered before [9]. Let us underline that in the present case, the unloading waves are connected not only with electrostriction but with the Coulomb forces, moreover, they are generated after the breakdown.

V. Conclusion

Thus, as a result of the experimental investigation of post-breakdown ionization processes in near-electrode conducting layers inside water, it has been found that near the cathode, in the space charge region a transverse (with respect to the channel) discharge propagating with the velocity ~10 km/s is formed. The estimations show that after breakdown a giant local field should appear due to redistribution of electric field and space charge influence. The wave of density perturbations moving from the anode is registered. Nonelectrode streamers appear at the bulk of liquid in places where electric field has maximal value.

References

[1] W. A. Stygar *et al.*, "Architecture of petawatt-class z-pinch accelerators," *Phys. Rev. Special Topics Accel. Beams*, vol. 10, pp. 1–24, Mar. 2007.

[2] V. V. Vorov'ev, V. A. Kapitonov, and E. P. Kruglyakov, "Increase of dielectric strength of water in a system with 'diffusion' electrodes," *JETP Lett.*, vol. 19, no. 2, pp. 58–59, 1974.

[3] E. V. Yanshin *et al.*, "Physical processes limiting the pulse energy release in liquid dielectrics," in *10th IEEE Pulsed Power Conf., Dig. Tech. Papers*, vol. 1. Jul. 1995, pp. 574–579.

[4] S. M. Korobeynikov, A. V. Melekhov, and V. G. Posukh, "Electrooptical measurements of the electric field strength in water with near-electrode conductive layers," *Doklady Phys.*, vol. 55, no. 8, pp. 391–393, 2010.

[5] S. M. Korobeynikov, A. V. Melekhov, V. G. Posukh, A. G. Ponomarenko, E. Boyarintsev, and V. M. Antonov, "Optical study of prebreakdown cathode processes in deionized water," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 16, no. 2, pp. 504–508, Apr. 2009.

[6] S. M. Korobeynikov and A. V. Melekhov, "Nonelectrode streamers in deionized water," *IEEE Trans. Plasma Sci.*, vol. 39, no. 11, pp. 2632–2633, Nov. 2011.

[7] E. V. Yanshin, K. V. Yanshin, and S. M. Korobeynikov, "Space charge and pre-breakdown bubbles formation near point electrodes under pulse voltage," in *Proc. 8th Int. Conf. Conduction Breakdown Dielectr. Liquids*, 1984, pp. 194–198.

[8] M. Zahn, Y. Ohki, D. B. Fenneman, R. J. Gripshover, and V. H. Gehman, "Dielectric properties of water and water/ethylene glycol mixtures for use in pulsed power system design," *Proc. IEEE*, vol. 74, no. 9, pp. 1182–1221, Sep. 1986.

[9] S. M. Korobeynikov and E. V. Yanshin, "Electrostriction pressure dynamics in a liquid near spherical electrode," *Sov. Phys. Tech. Phys*, vol. 28, pp. 1288–1291, Feb. 1983.

Authors' photographs and biographies not available at the time of publication.