Simulation of prebreakdown fields in water

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Introduction

Synthesis of optics and electrophysics performs to get new data concerning physical processes that take place in liquid at the action of high voltage. These processes precede liquid breakdown. Usually breakdown of liquids initiates on electrode and develops in the direction of opposite electrode as filament or bush-like structures. Discharge channel originated inside bulk of liquid didn’t register before. Moreover electrical breakdown occurs only at the action of voltage. Discharge channel in liquid originated past the voltage action didn’t register before too.

Outline

- 1. Introduction to Kerr effect
- 2. Streamers
- 3. Attempts of pulse electrical strength increase.
- 4. Electric fields simulations

What is it: Kerr effect?

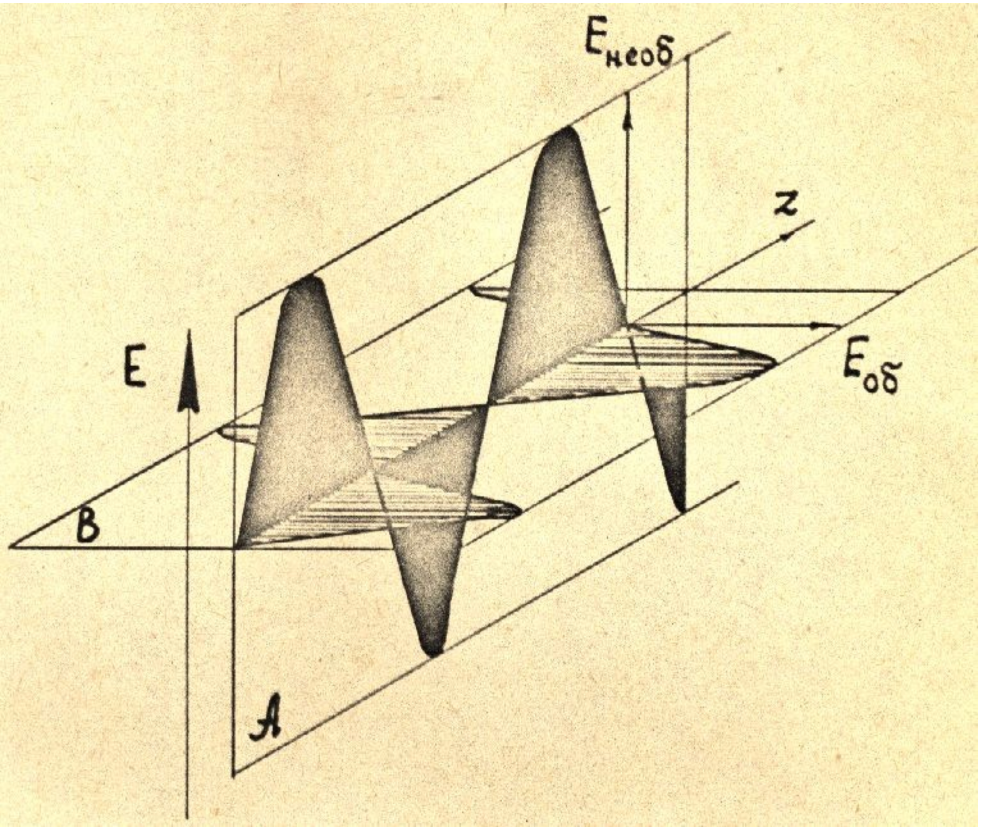
This is obtaining of liquid the optical properties of uniaxial crystall with optic axis oriented along the electric field

$$n_e = n_0 + 2/3\cdot\lambda B\cdot E^2$$

$$n_o = n_0 - 1/3\cdot\lambda B\cdot E^2$$

n_e - refractive index of extraordinary ray
n_o – refractive index of ordinary ray
n_0 – n_0 – refraction index in the case of zero field
λ- wavelength of light
B- Kerr constant, for nitrobenzene B = 2.4 10^{-10} cm/V^2, for water E – 2.6 10^{-12} cm/V^2

Polarization of light in extraordinary and ordinary waves

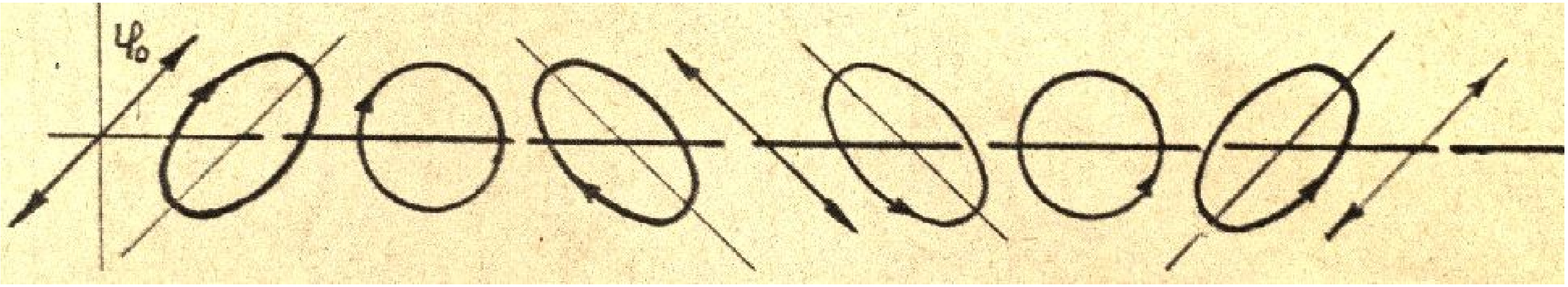


Extraordinary – E_{wave} II E_{macro} Ordinary –$E_{wave} \perp E_{macro}$

Phase Shift and Intensity of Passed Light

- $V_e=C/n_e$ $V_o=C/n_o$
- $\Delta\Gamma=2\pi(n_e - n_o)\cdot l/\lambda$
- $\Delta\Gamma=2\pi B\cdot l\cdot E^2$
- $\mathbf{I}= \mathbf{I}_0 \sin^2(\Delta\Gamma/2)$ – crossed polarizers

Polarization Change during Move of Light Wave Polarized by 45 to Electric Field

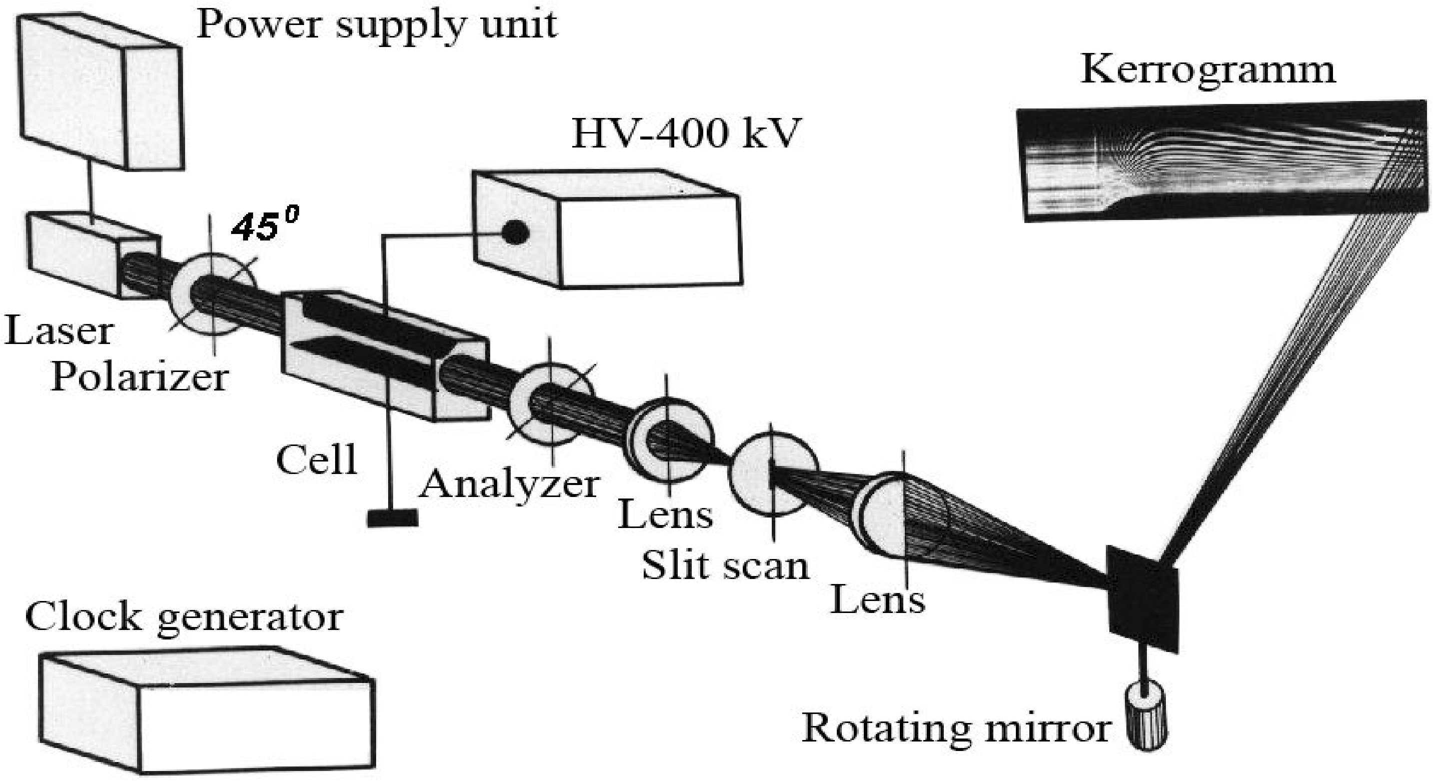


Measurement of Inhomogeneous Electrical Fields

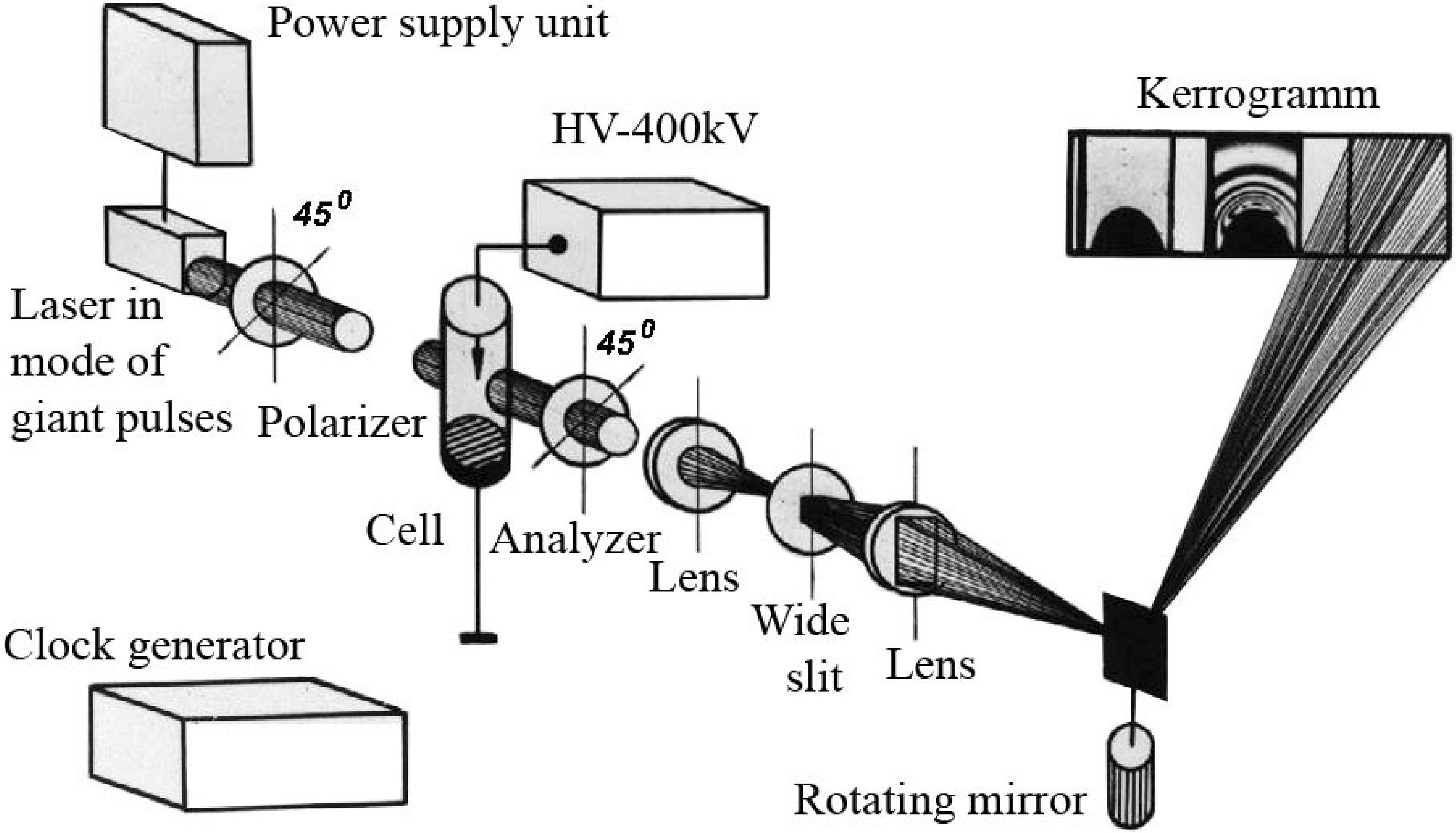
- $\Delta\Gamma(x,y) = 2\pi B \cdot \int E_{\perp}{}^{2}(x,y)\,dl$
- $\mathbf{I(x,y)} = \mathbf{I}_0 \sin^2(\Delta\Gamma(x,y)/2)$
- On the x,y plane the lines:
- $\Delta\Gamma(x,y)/2 = \pi/2 + \pi \cdot k$ form light fringes

  $\Delta\Gamma(x,y)/2 = \pi \cdot k$ form dark fringes
- Each of fringe corresponds to some average electric field. Knowing stripes distribution, intensity distribution can be defined.

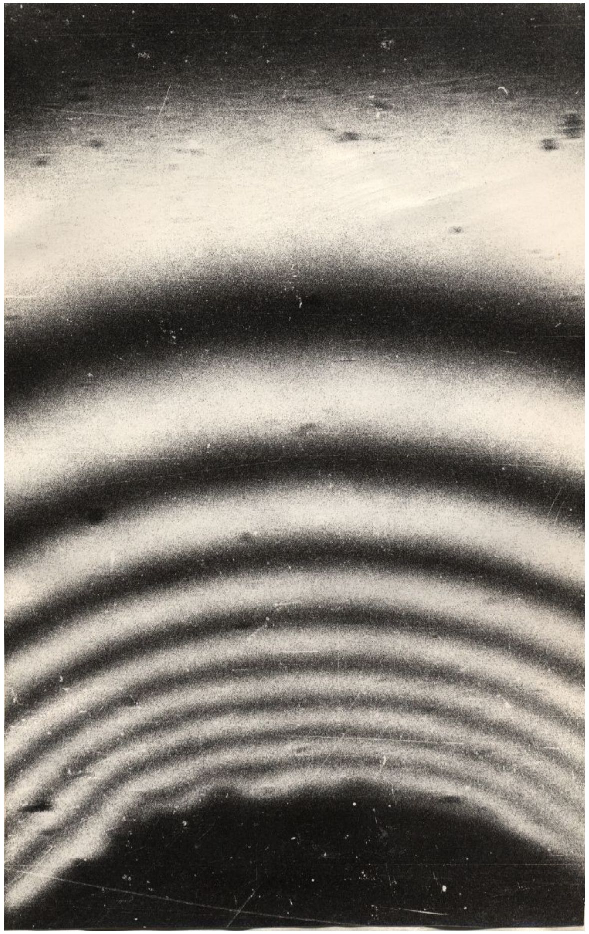
Experimental Setup for Fields Investigation. Slit scan.



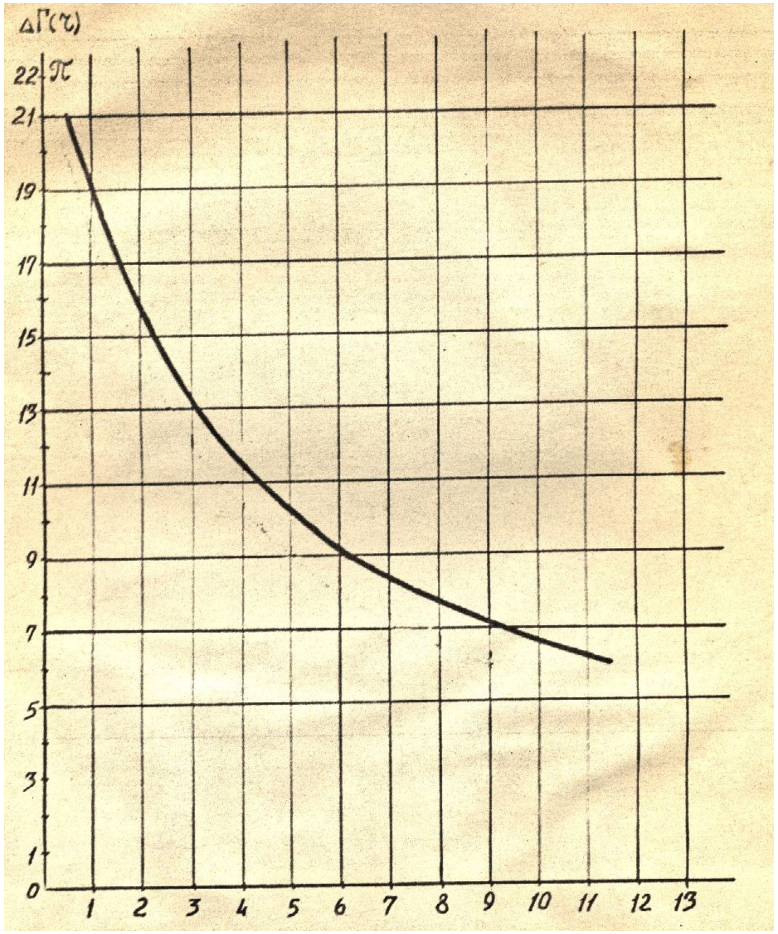
Experimental Setup for Fields Investigation. Generation of Images.



Distribution of Kerr Fringes near Needle Electrode

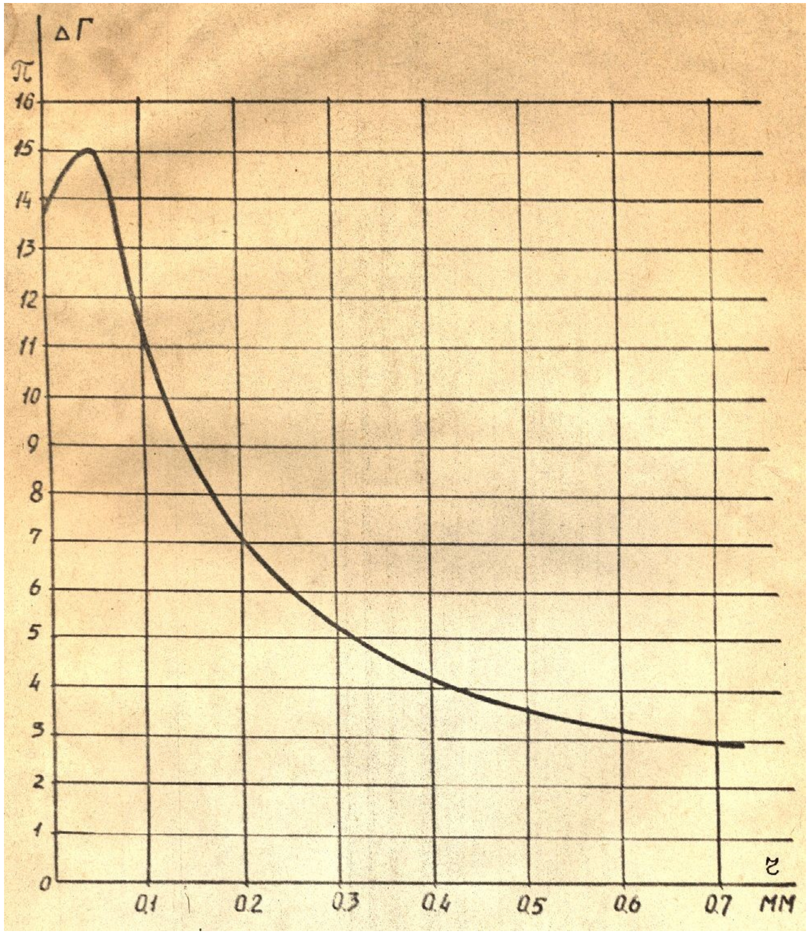


Distribution of Phase Shift Near Electrode

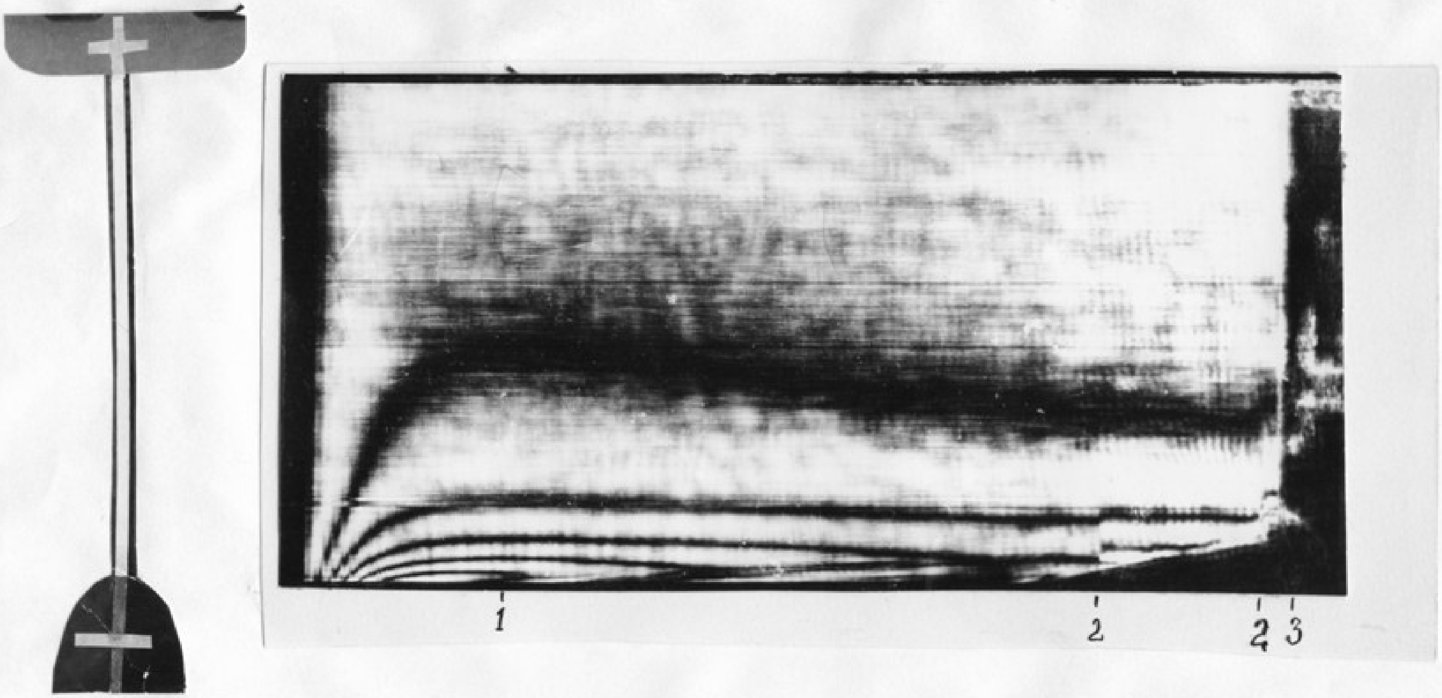


Kerr Fringes with Phase Decrease Near Electrode Surface

Distribution of Phase Shift Near Electrode

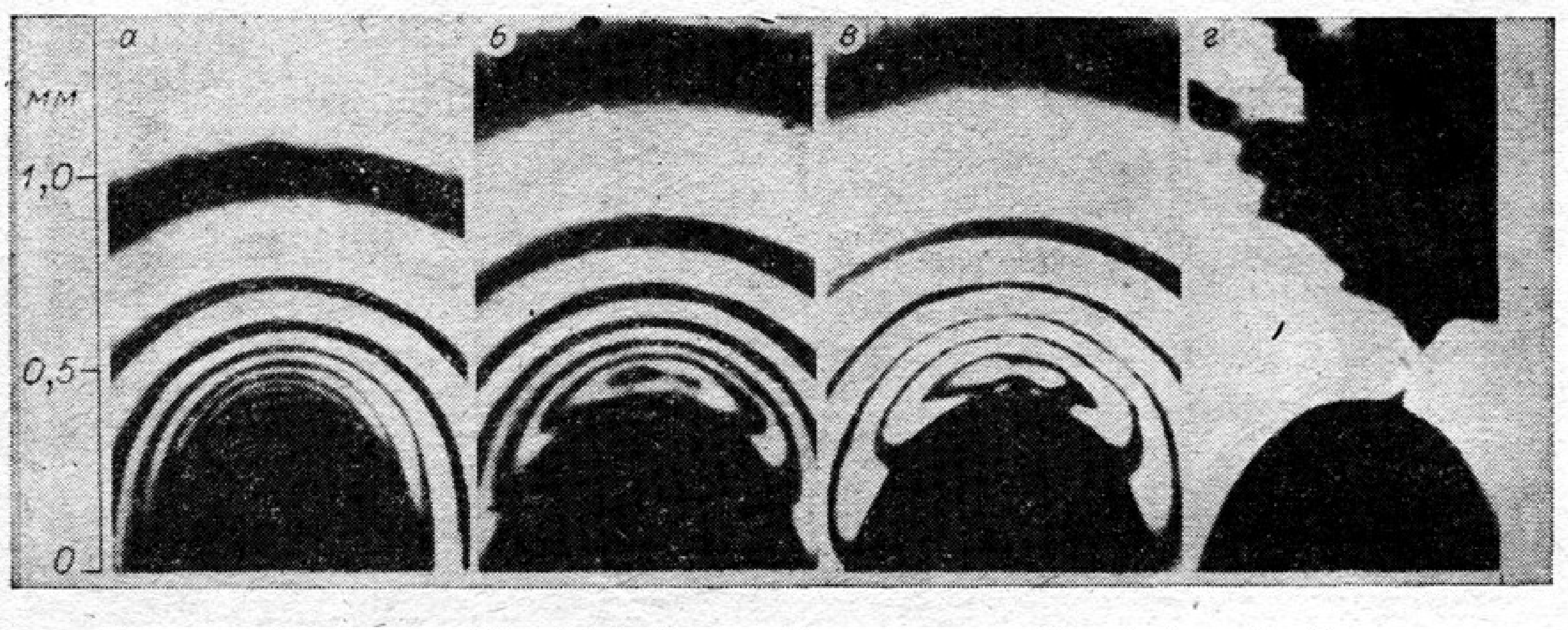


Kerr fringes in case of needle cathode in nitrobenzene. Slit scanning



1- first bubble appearance;
2- two events of local discharges in bubble zone;
3- breakdown initiation

Kerr fringes. Images.



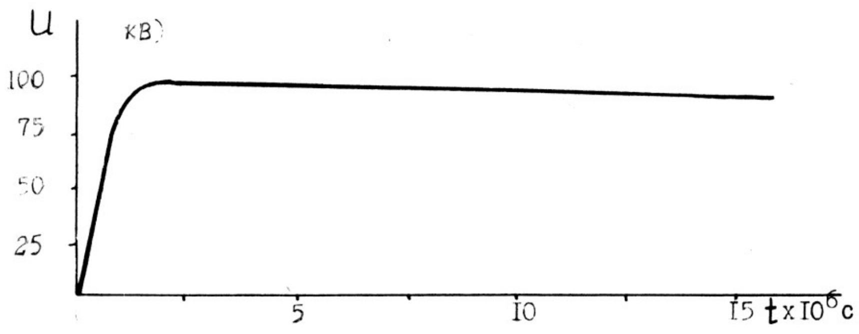
Space charge and bubble formation near cathode in nitrobenzene

Pictures at 1.2 mks, 2.6 mks, 4.5 mks, 10 mks voltage action

ELECTROHYDRODINAMICAL PROCESSES & INJECTION

Kerr fringes with slit scanning perform to see both electric field and charge injection, charge carriers and bubbles movement.

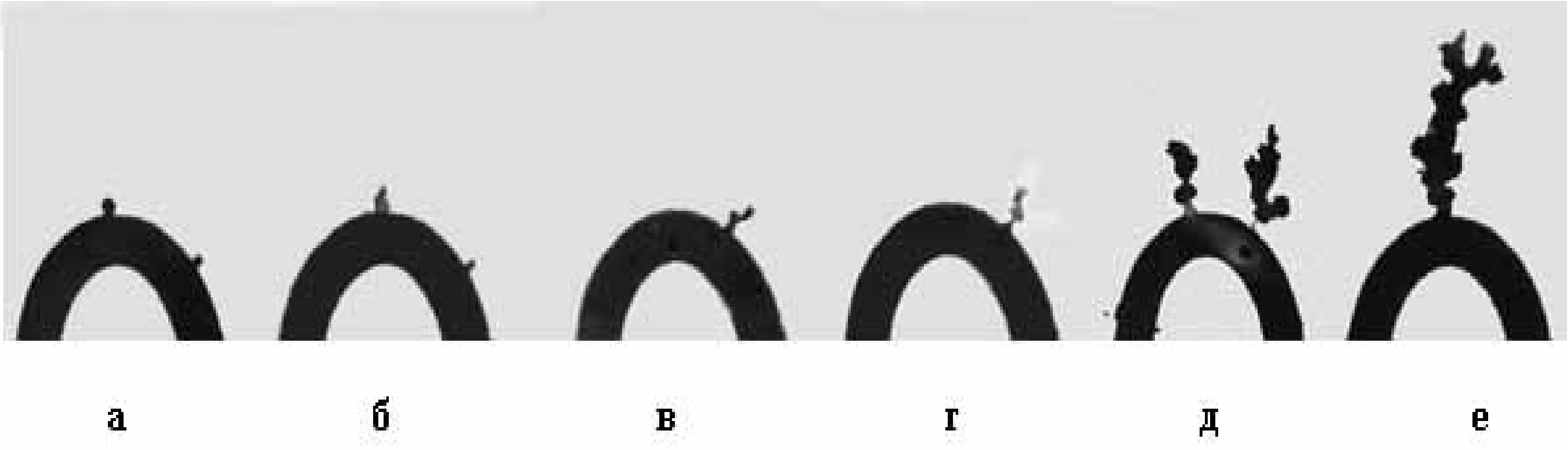
The velocities of charge carriers and bubbles approximately equals one to other. And well correspond to EHD velocity!!



Streamers

Streamers

It is well known, cathode streamers originates at electrode and usually develops as bush-like opaque structure with velocity less than sound velocity.



Charge's ignition on a cathode begins with a bubble's elongation, then it becomes to look like a mushroom, and at the end subsonic streamer grows into a bush.

Picture of tree propagation

The tree is a self–similar developing construction.

Every branch develops and it is divided into series of new branches which in their turn develop and they are also divided, and so on.

Some branches do not develop. Especially, it concerns the branches inside the tree.

What mechanism could be?

Velocity estimation

- Assuming that the movement of the branch tip has EHD nature, one can estimate their velocity V
- $\rho \cdot V^2 \sim \alpha \cdot \varepsilon_0 \cdot \varepsilon \cdot E^2$,
- where ρ is the liquid density, ε·is the dielectric permittivity, α is the part of electrical energy that transforms into a hydrodynamic one. Numerical evaluation of V after substitution of $\alpha \sim 0.1$, $\varepsilon = 80$, $\rho = 1$ T/m^3, E~10÷20 MV/cm gives V~300-600 m/c. This value does not contradict experimental values $V \leq 10^3$ m/c.
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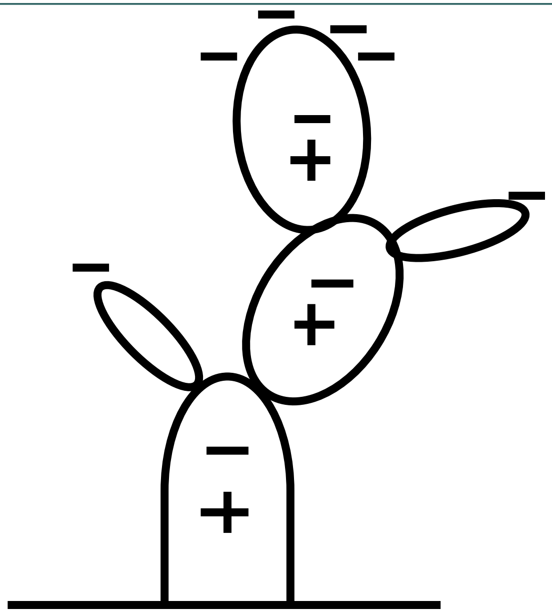
POSSIBLE MODEL OF CATHODE TREE PROPAGATION

- 1. Discharge in microbubbles. Charging of the bubble surface.
- 2. Instabilities of charged surface.
- 3. Developing of instabilities. More size – more velocity.
- 4. EHD movement of charged protuberances.
- 5. Next instabilities.

Schematic diagram of prebreakdown processes



Cathode

Instability wave length of charged surface

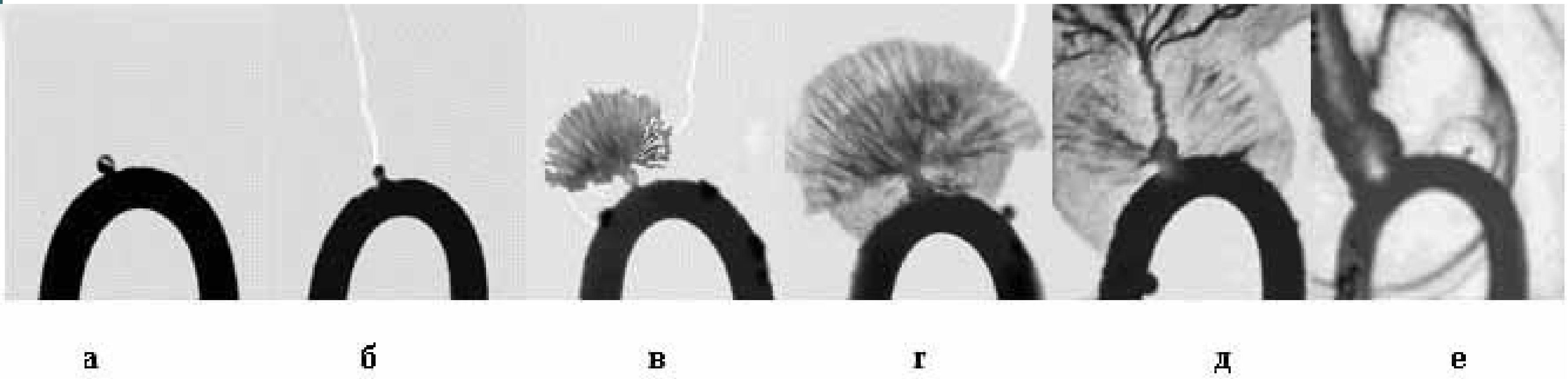
$$\lambda = \frac{4\pi \cdot \sigma}{\varepsilon_0 \varepsilon \cdot E^2}$$

$$\delta_\sigma \leq\leq \iota \leq\leq \cdot$$

$$\rho V^2/2 \approx \alpha \cdot \varepsilon \cdot \varepsilon_0 \cdot E^{*2}/2$$

For E* ~ 10 MV/cm and $\alpha \approx 0.1$-0.9 one could get V ≈ 300-900 m/sec. This value don’t contradict to experimental data V ≈ 500-600 m/sec.

Anode streamers develops as filament structure with velocity much more than sound velocity



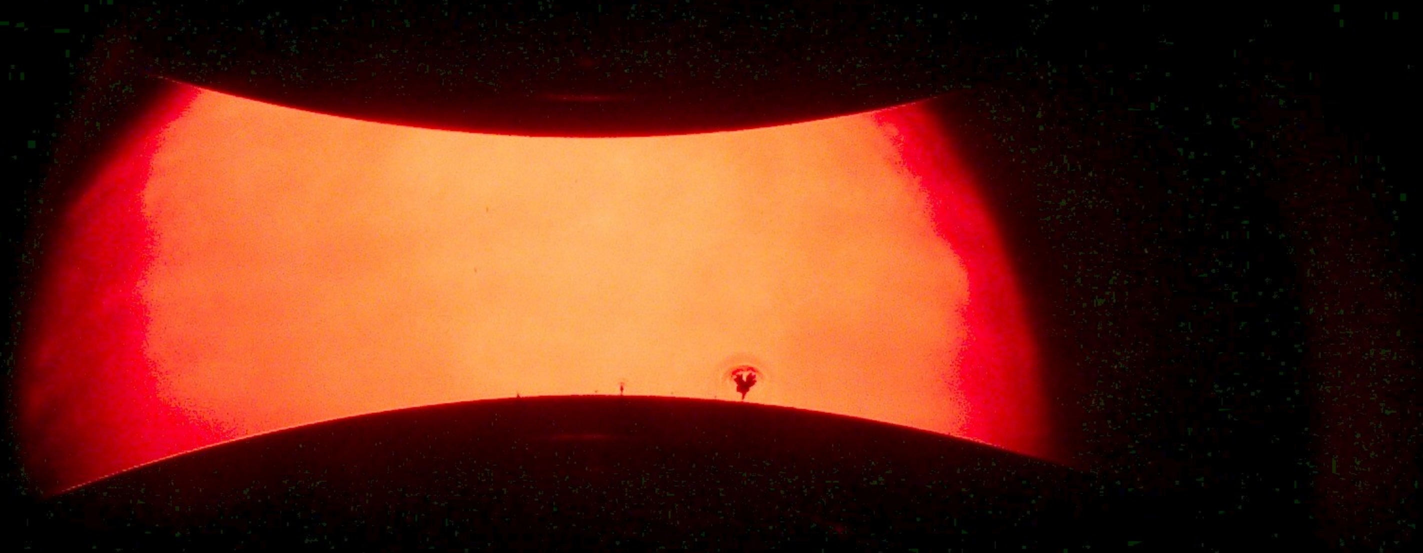
Discharge’s ignition on an anode is accompanied by bubbles’ elongation, appearance of supersonic streamers’ set, their disappearance, 2nd set of streamers, which is finished by gap shortening.

Suitable model for breakdown channel propagation is absent till now.

Moreover, conductivity of channel, electric field intensity close to the tip of the channel are unknown.

Prebreakdown cathode streamer. Kerrogram (ph

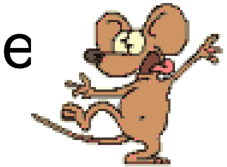
Bare electrodes



One could see cathode streamer only with one or two Kerr fringes

Anode modified. Bare cathode.

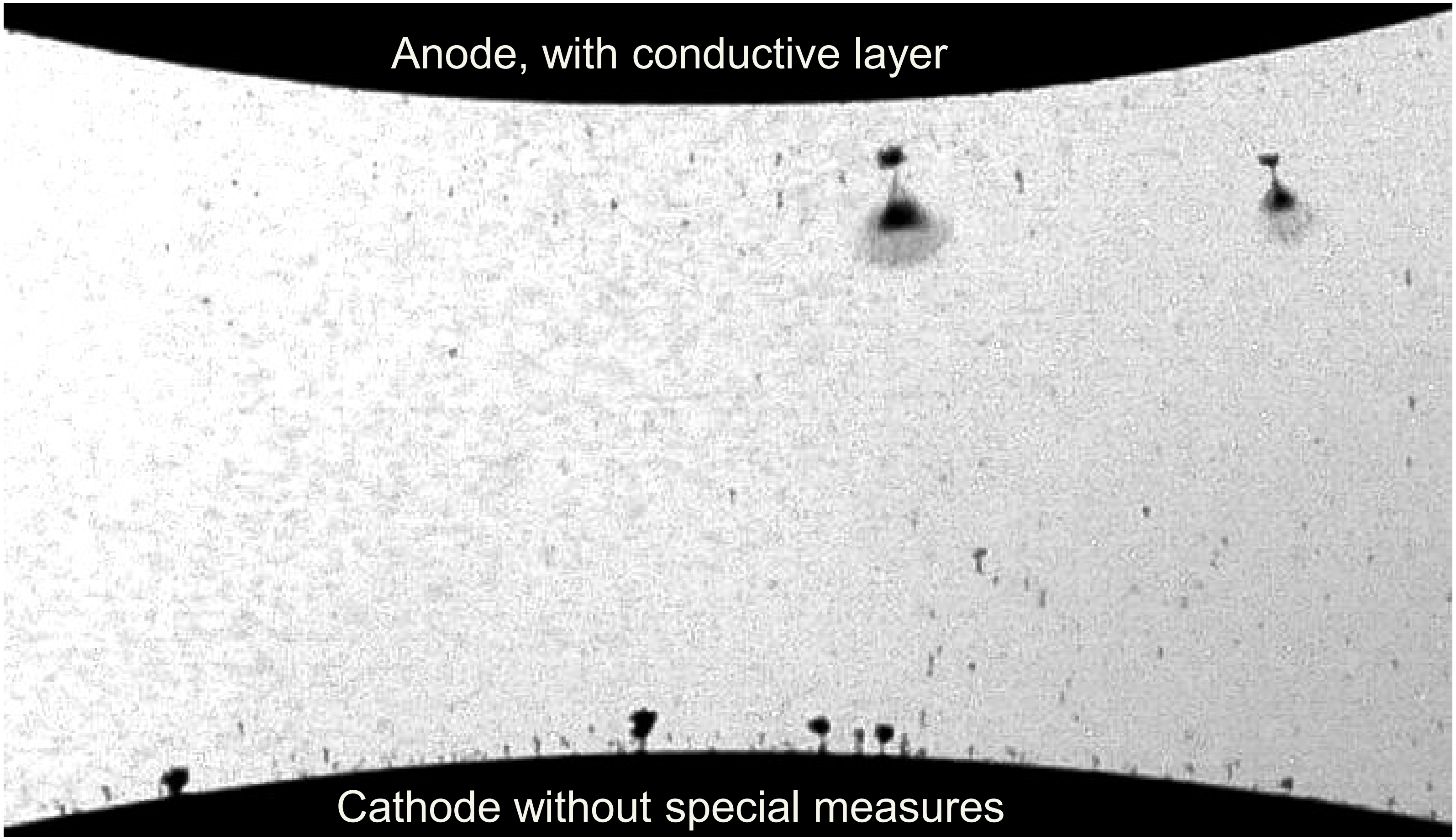
Big prebreakdown streamers from cathode



E_{av} = 450 kV/cm.

One could see bulk initiated streamer.

Nonelectrode streamers



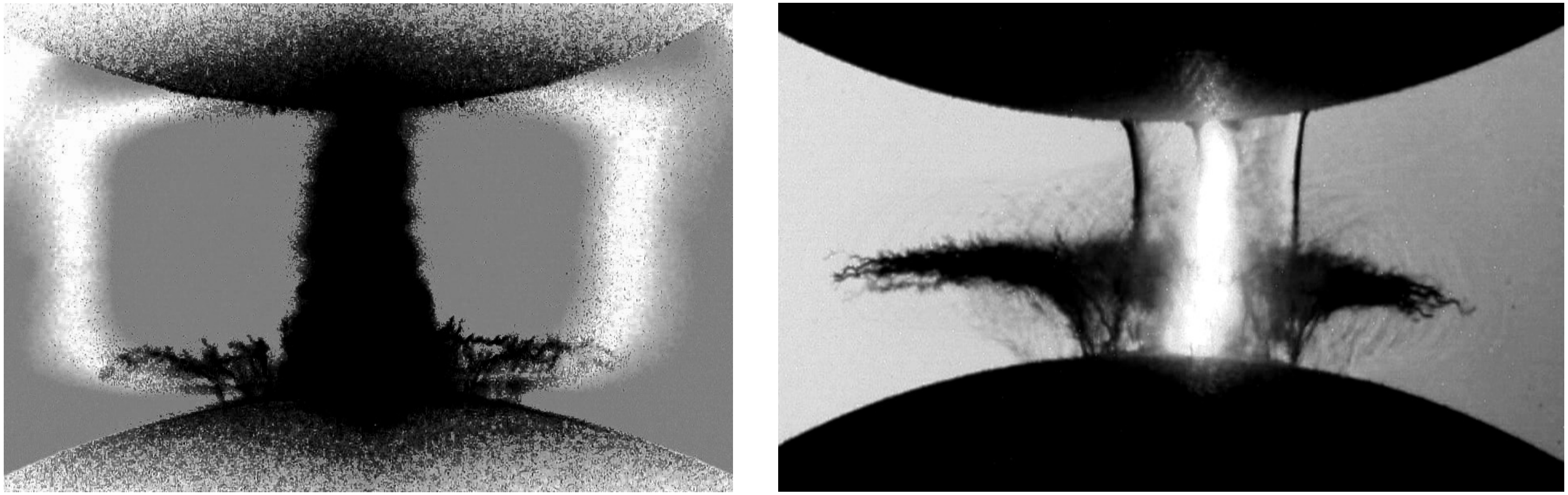
Cathode oriented semistreamer like usual anode streamer (slide 17).
Anode oriented semistreamer like usual cathode streamer (slide 16).

Big nonelectrode streamer touches cathode

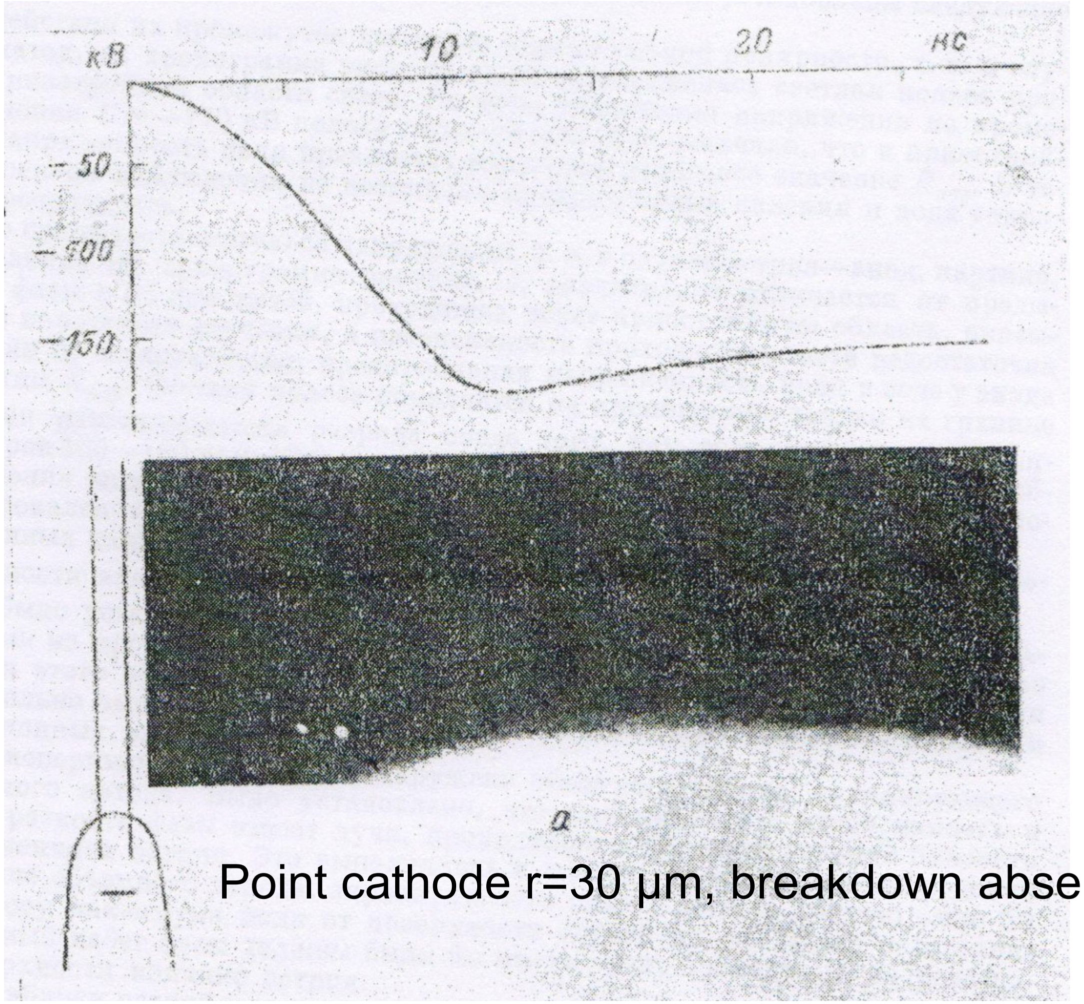
Picture at the breakdown moment

Near cathode – three nonelectrode streamers

Kerrogram and shadow image of postbreadown streamers



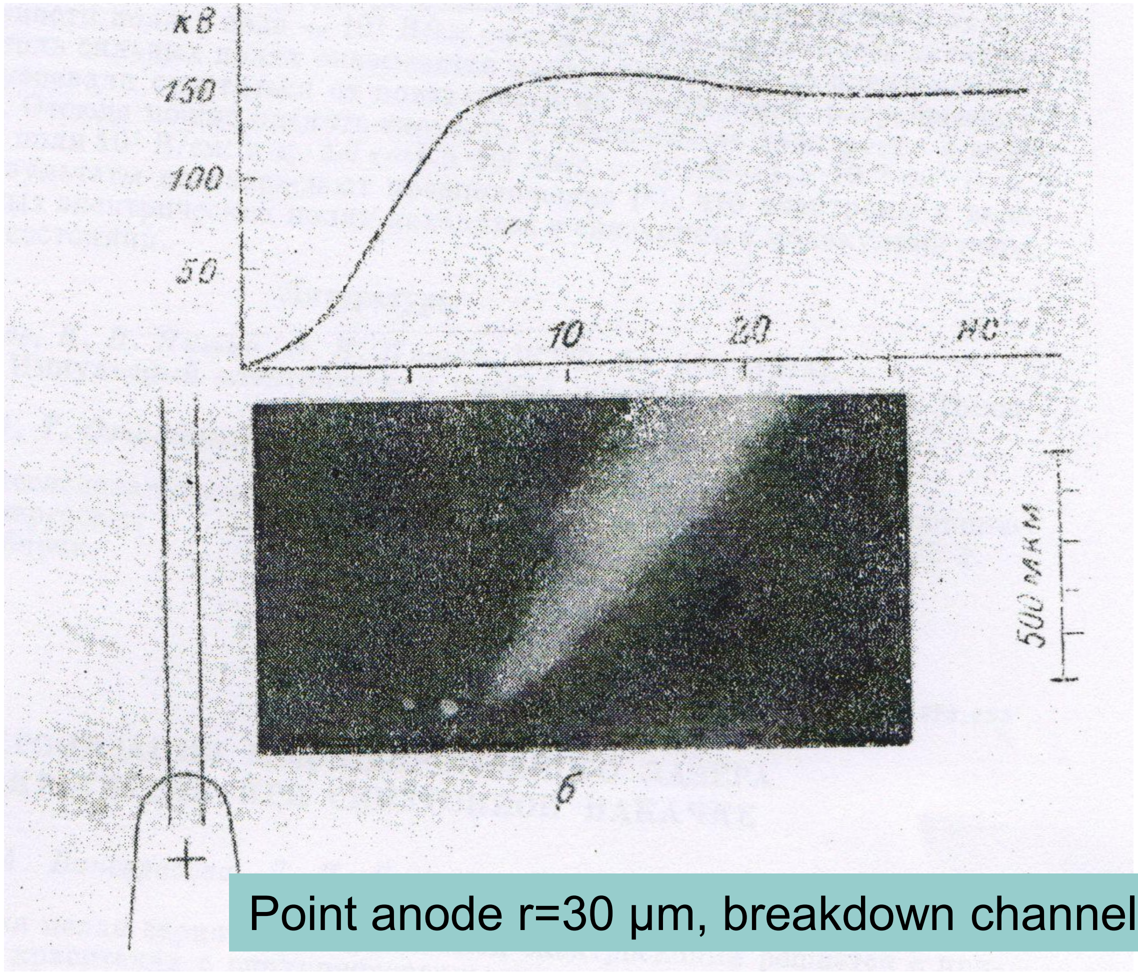
Kerr fringe in water with point electrode



Point cathode r=30 μm, breakdown absent

Electric field close to electrode exceeds 10 MV/cm!

Kerr fringe in water with point electrode



Point anode r=30 μm, breakdown channel with Kerr fringe

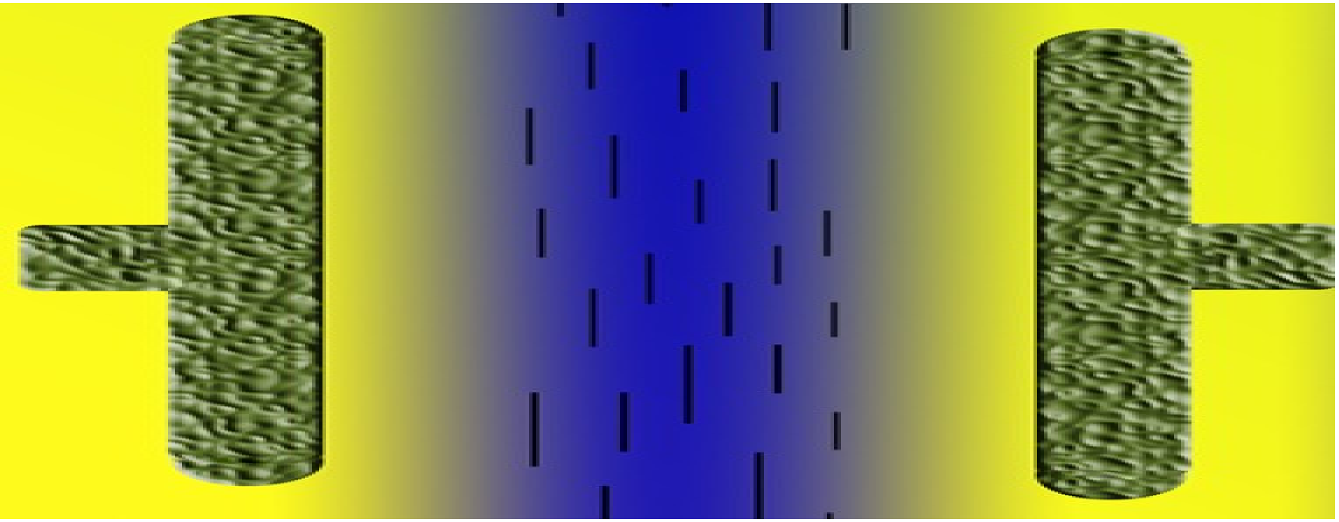
Streamer field is high. It looks like conductive sphere on the tip of electrode

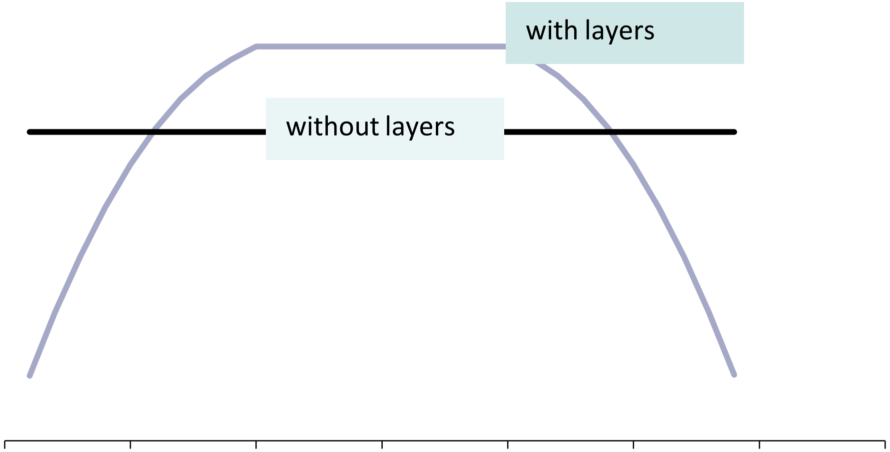
Attempts of pulse electrical strength increase

Attempts of pulse electrical strength increase

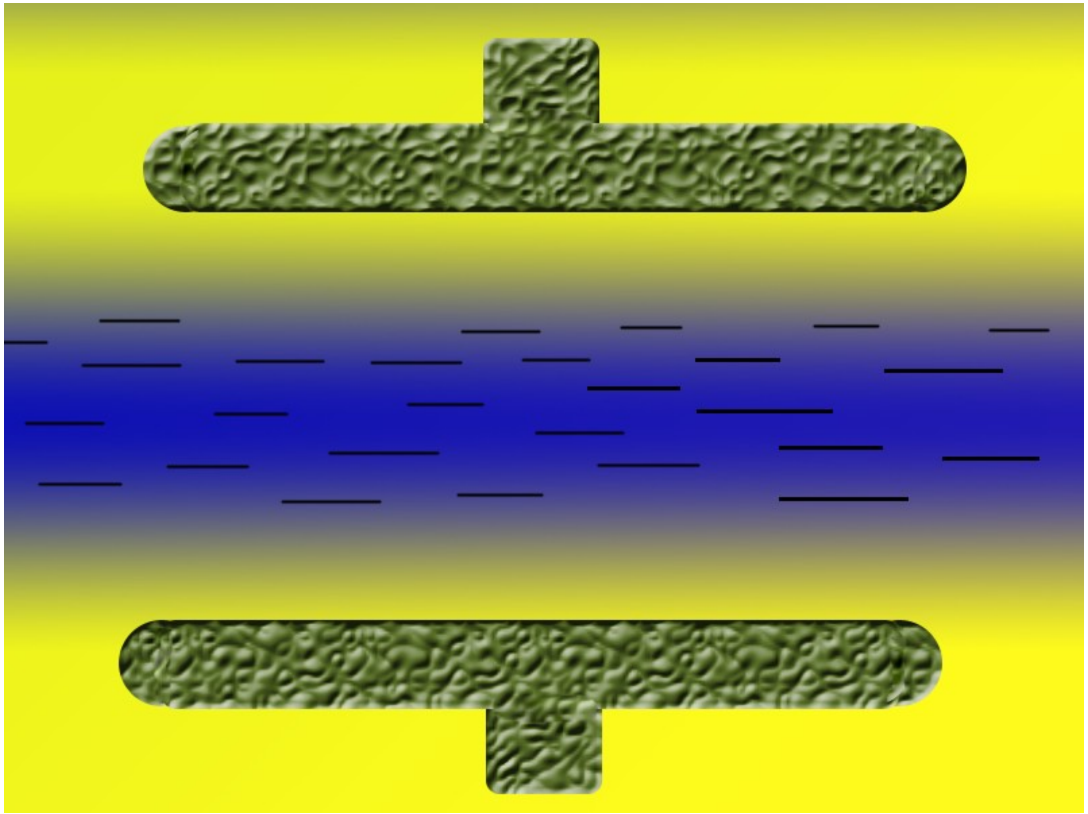
The single effective method of pulse electrical strength increase of liquids is formation of conductive layers near electrodes.
I know two successful attempts: in water with the help of electrolyte forcing through porous electrodes and in glycerol by pulse heating of hollow electrodes.

Electric field inside gap with and without conductive layers



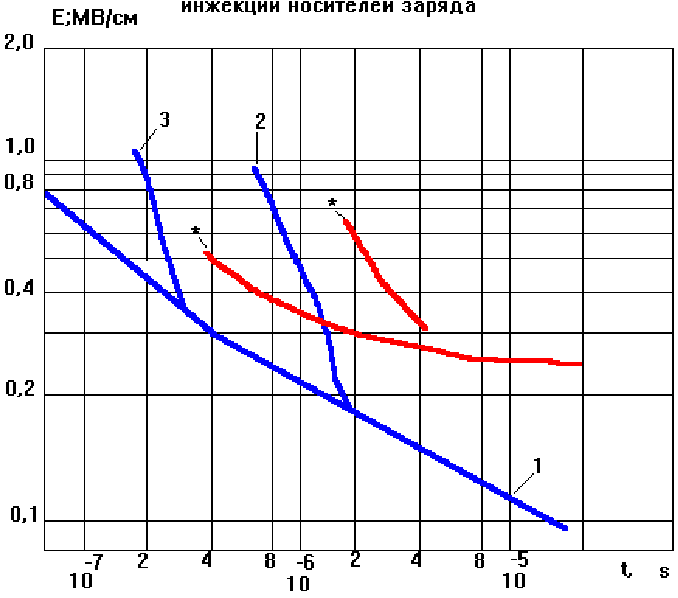


“Diffusion” electrodes in water



First succesful attempts of pulse electrical strength increase

Вольтсекундные характеристики для воды при учете
инжекции носителей заряда



1 - Пробой с анода

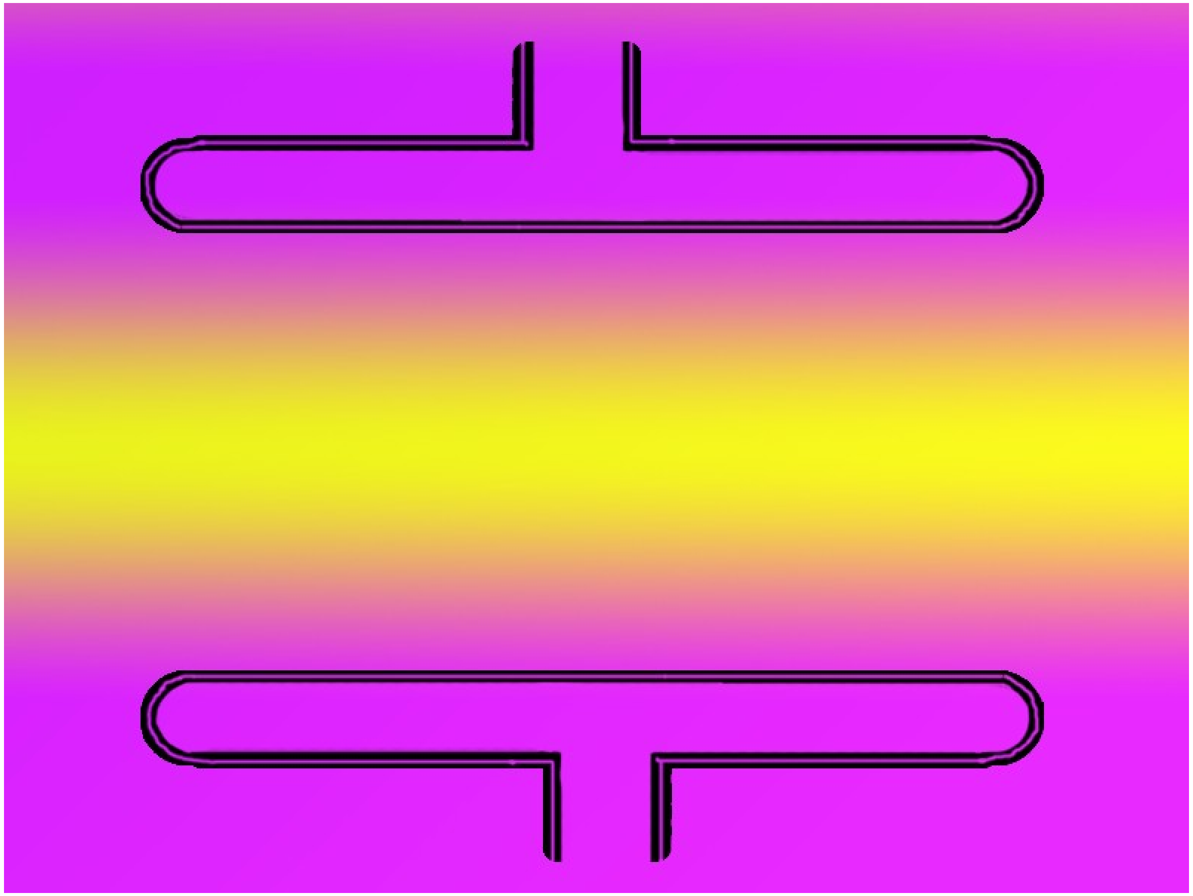
2,3 - пробой с катода ; 2 - E=0,2 MB/cm;3 - E=0,3 MB/cm

*- Красным- эксперименты ИЯФ с "диффузионными электродами'

First experiments were fulfilled by E.P. Kruglyakov with coauthors from INP SB RAN

The conductive layers are formed by forcing of electrolytes through porous electrodes.

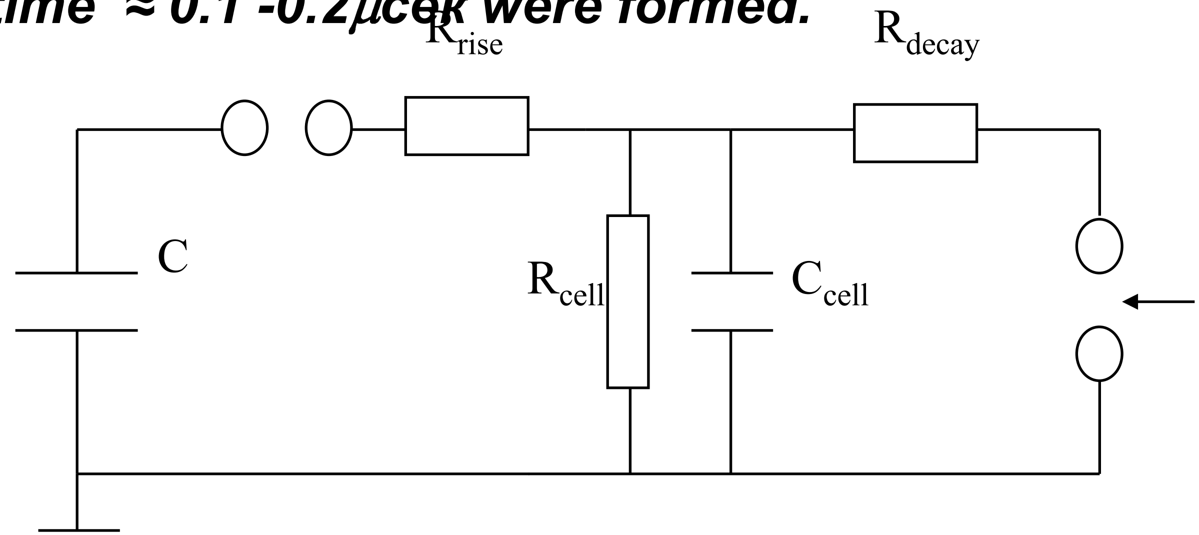
Pulse heated electrodes in glycerol



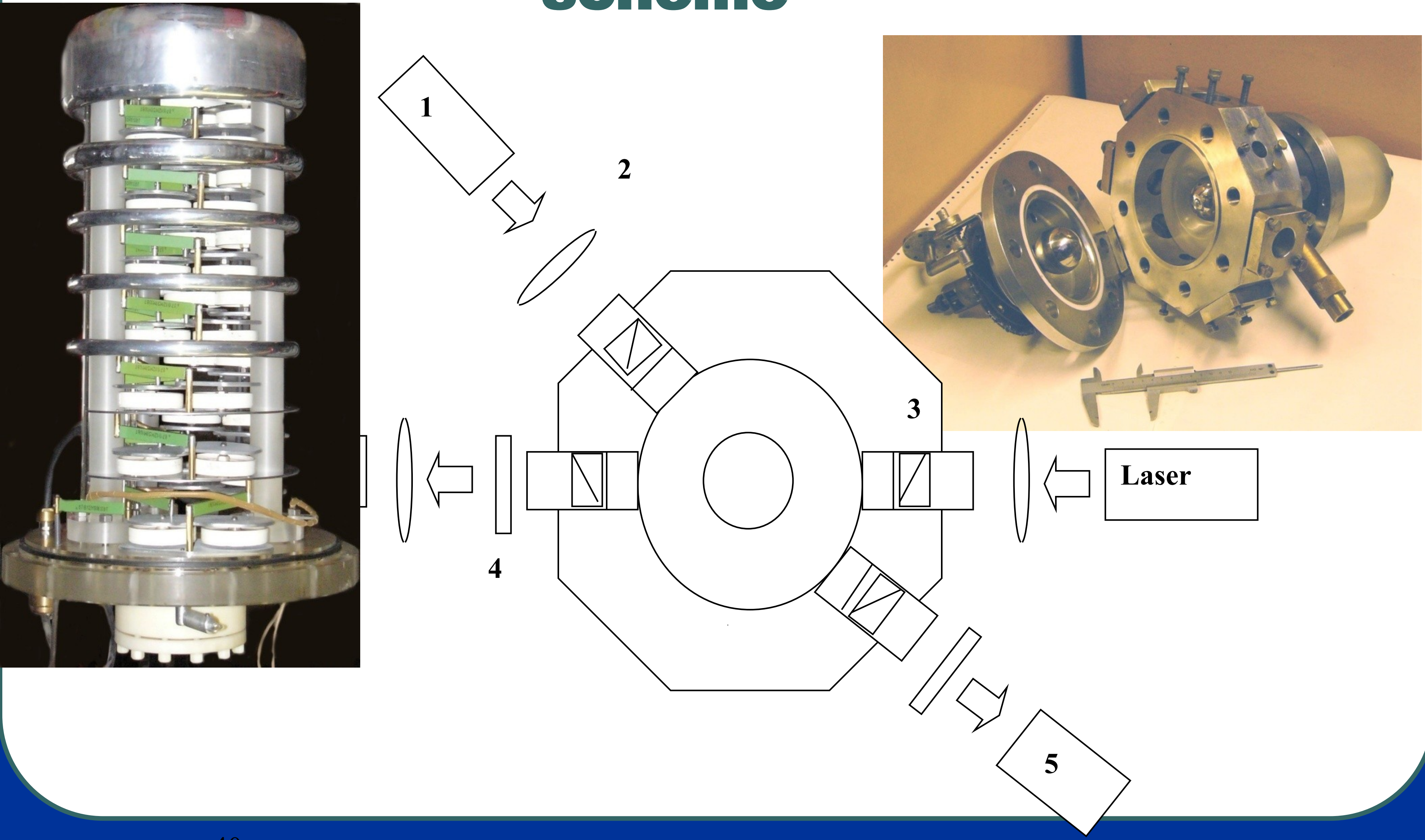
OUR ATTEMPT

Experimental setup

- *Triangle voltage pulses with rise time ≈ 1-2 μсек and decay time ≈ 0.1 -0.2μсек were formed.*



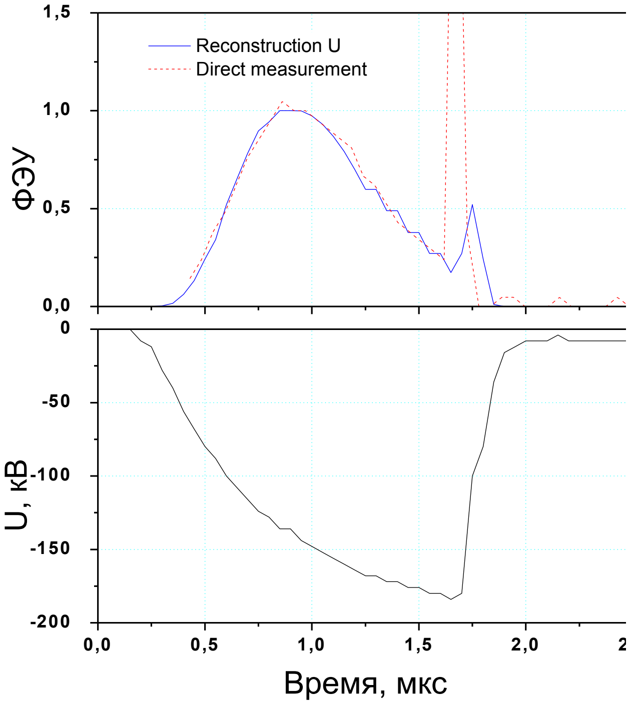
HV generator, cell and optical scheme

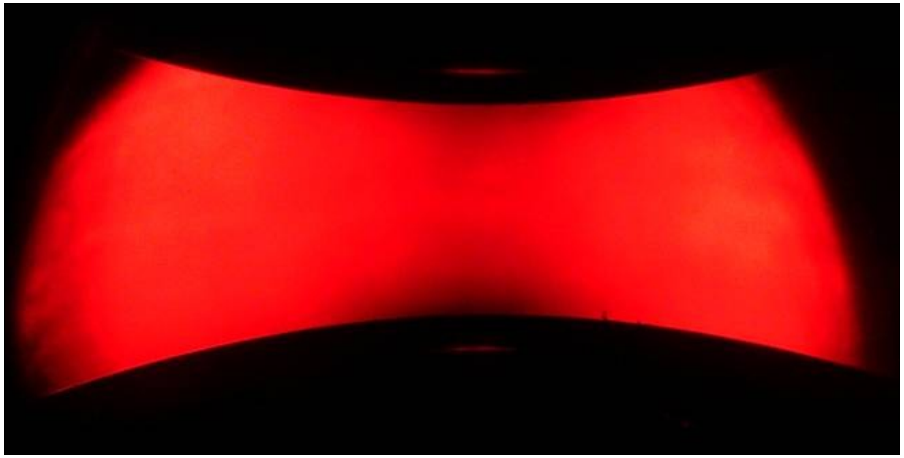


Modified electrode

Special membrane is on the metal electrode. Dark spots show tracks of four previous discharges.

Kerrogram (photo), oscillogram and signal from photomultiplier



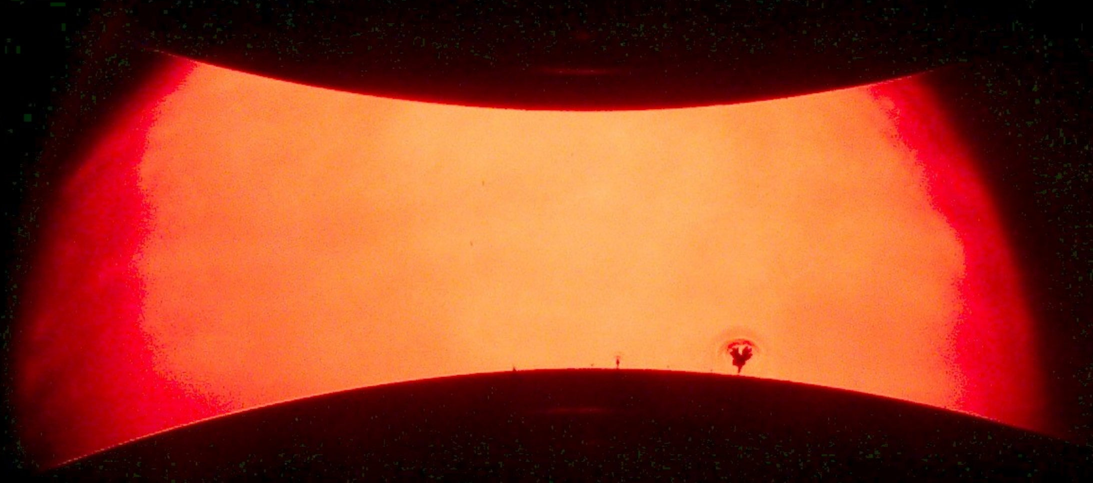


Crossed polarizers

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

Prebreakdown cathode streamer. Kerrogram (ph

Bare electrodes



Anode modified. Bare cathode.

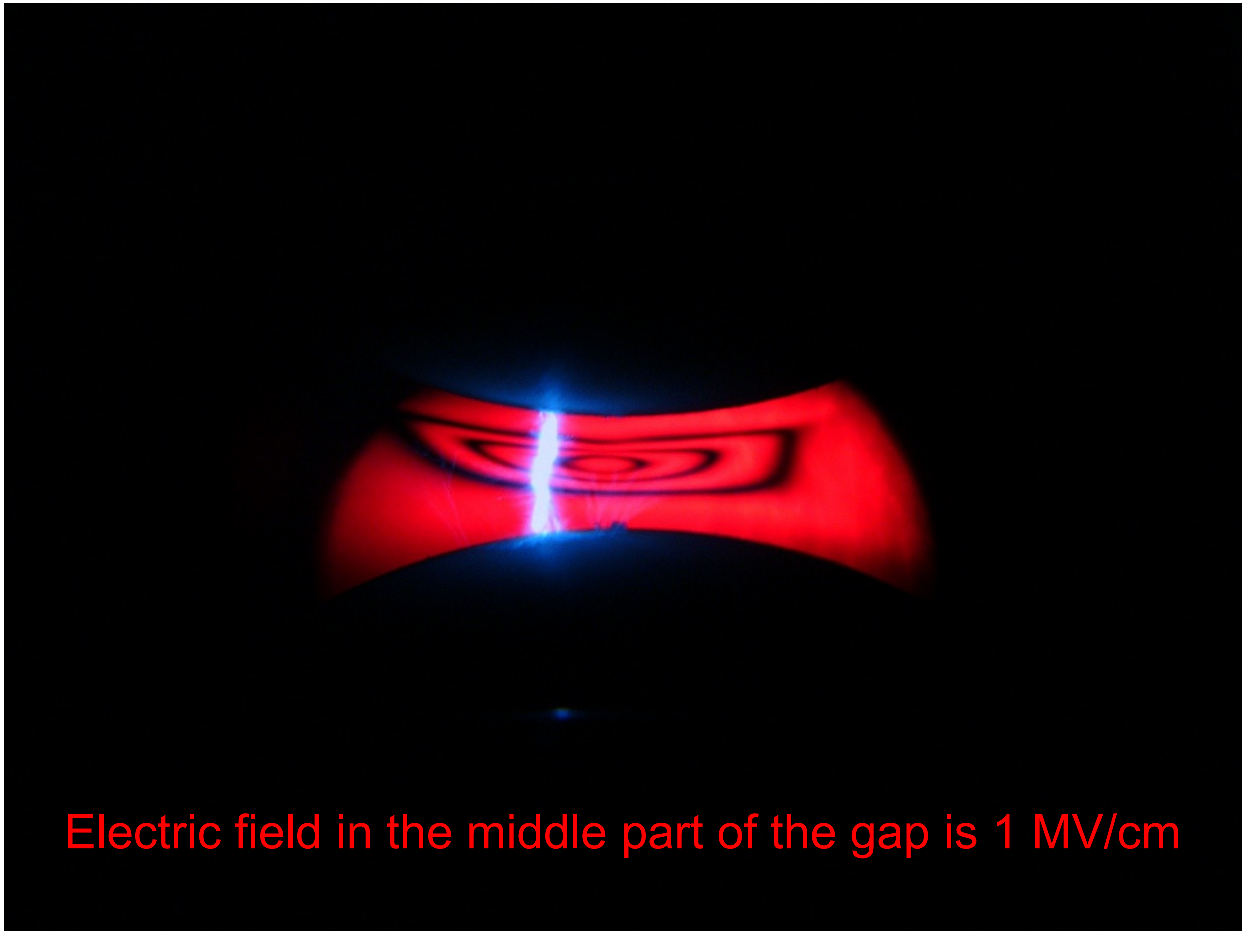
Prebreakdown streamers from cathode.

E_{av} = 450 kV/cm.

One could see bulk initiated streamer.

Electric field imaging.

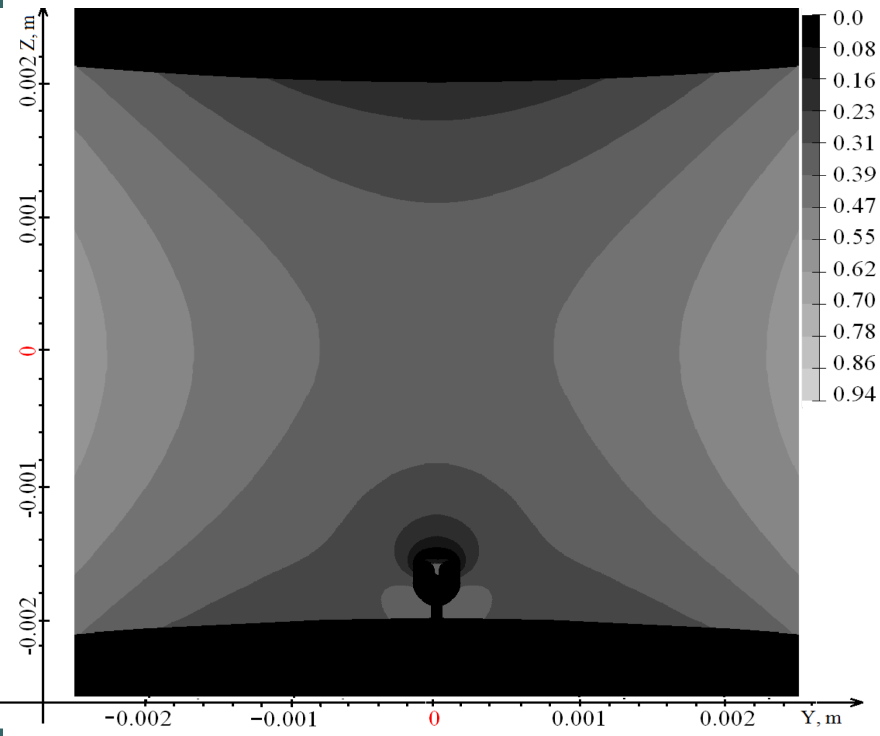
Conductive layers both near cathode and anode

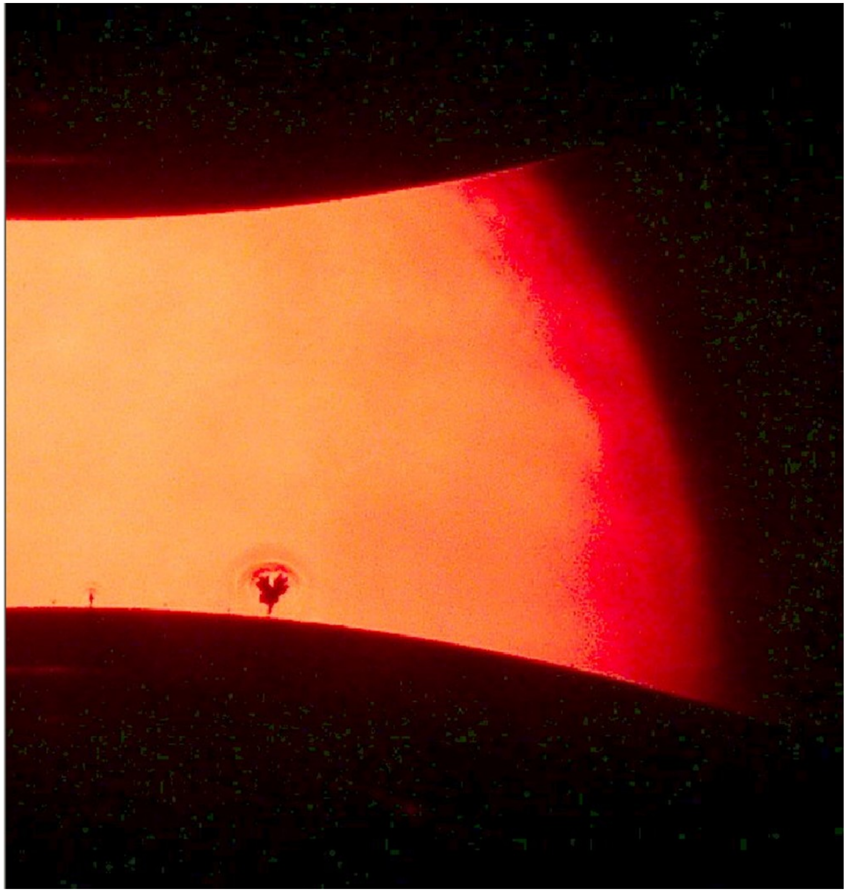


Electric field in the middle part of the gap is 1 MV/cm

Simulations and discussion

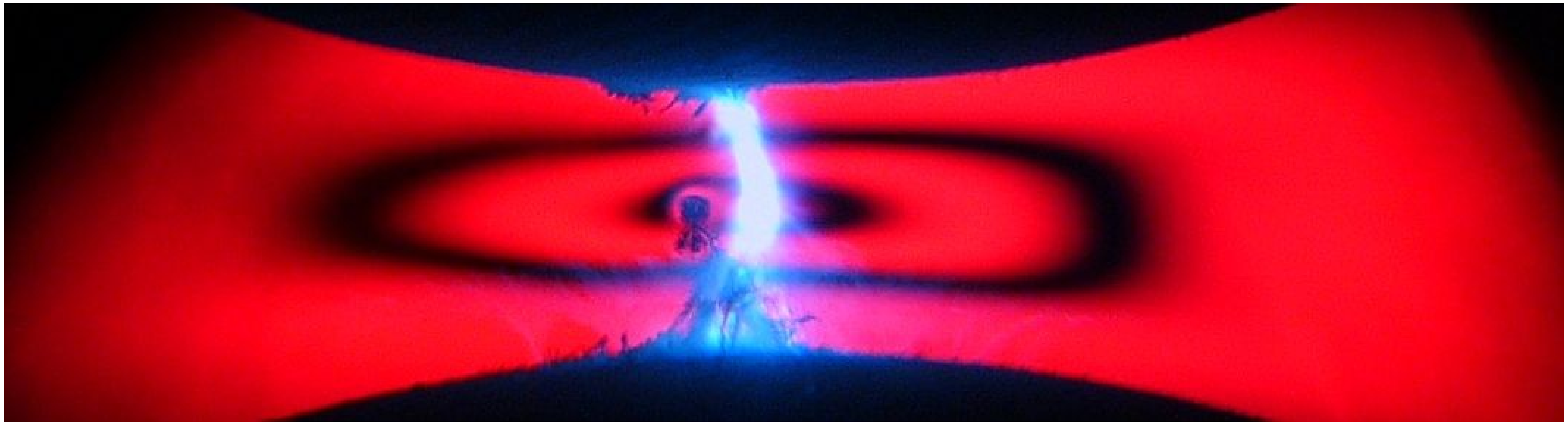
Comparison of computed Kerr fringes with experimental data for anode oriented small streamer on cathode





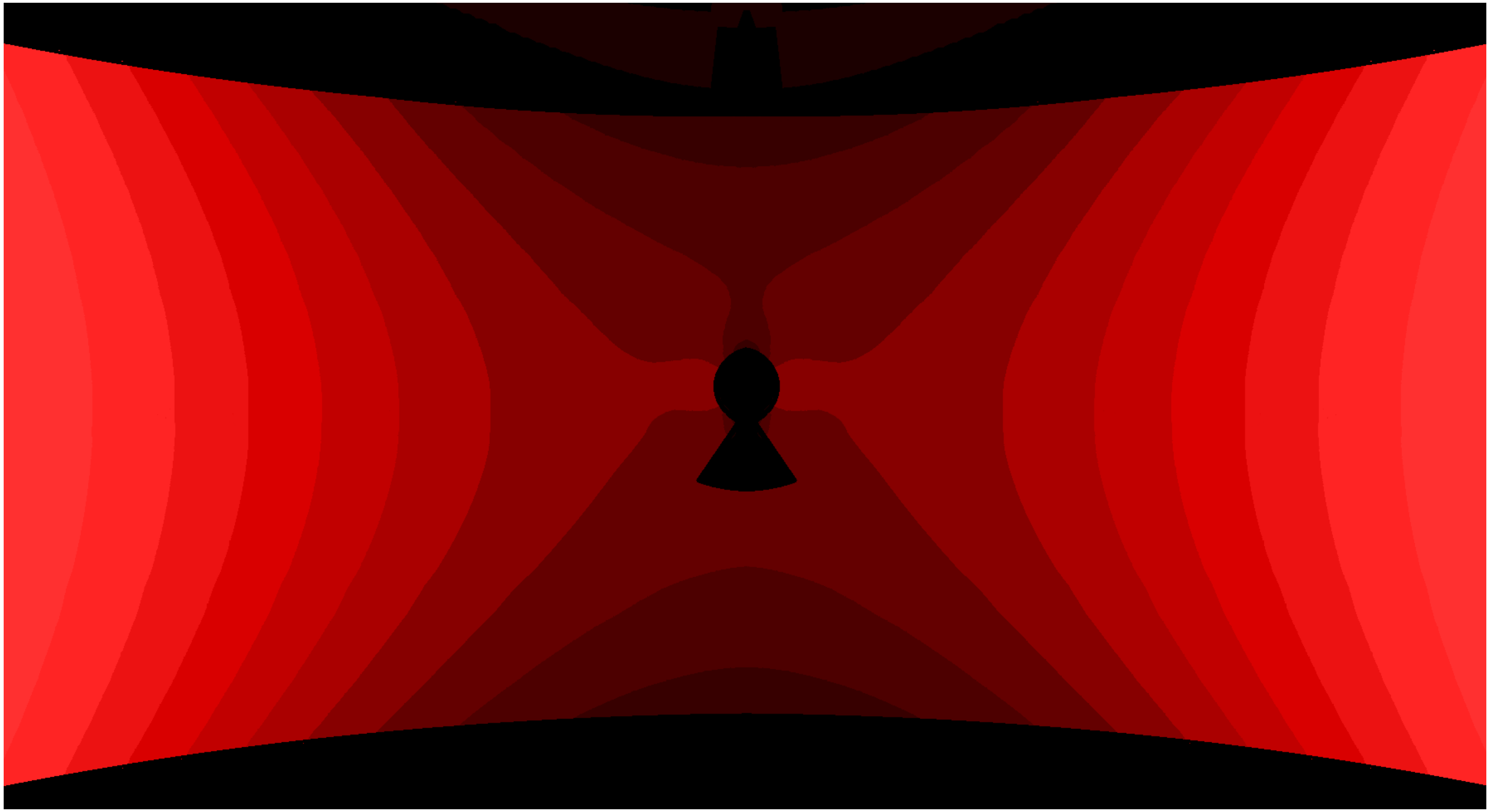
Simulations of streamer as conductive body give one Kerr stripe only

Superposition of breakdown light and Kerr fringes



In the center of the gap there is nonelectrode streamer. Electric field near anode oriented part is increased. Near cathode oriented part – without change.

Simulation of nonelectrode streamer



Streamer field estimations

Computer simulation of Kerr fringes perform to estimate electric field.

Macroscopic field near cathode streamer estimated as ≈ 2 MV/cm, so macroscopic field near anode streamer could be estimated less than 400 kV/cm.

Macroscopic breakdown field near electrode is 400-450 kV/cm both with conductive layers and without layers.

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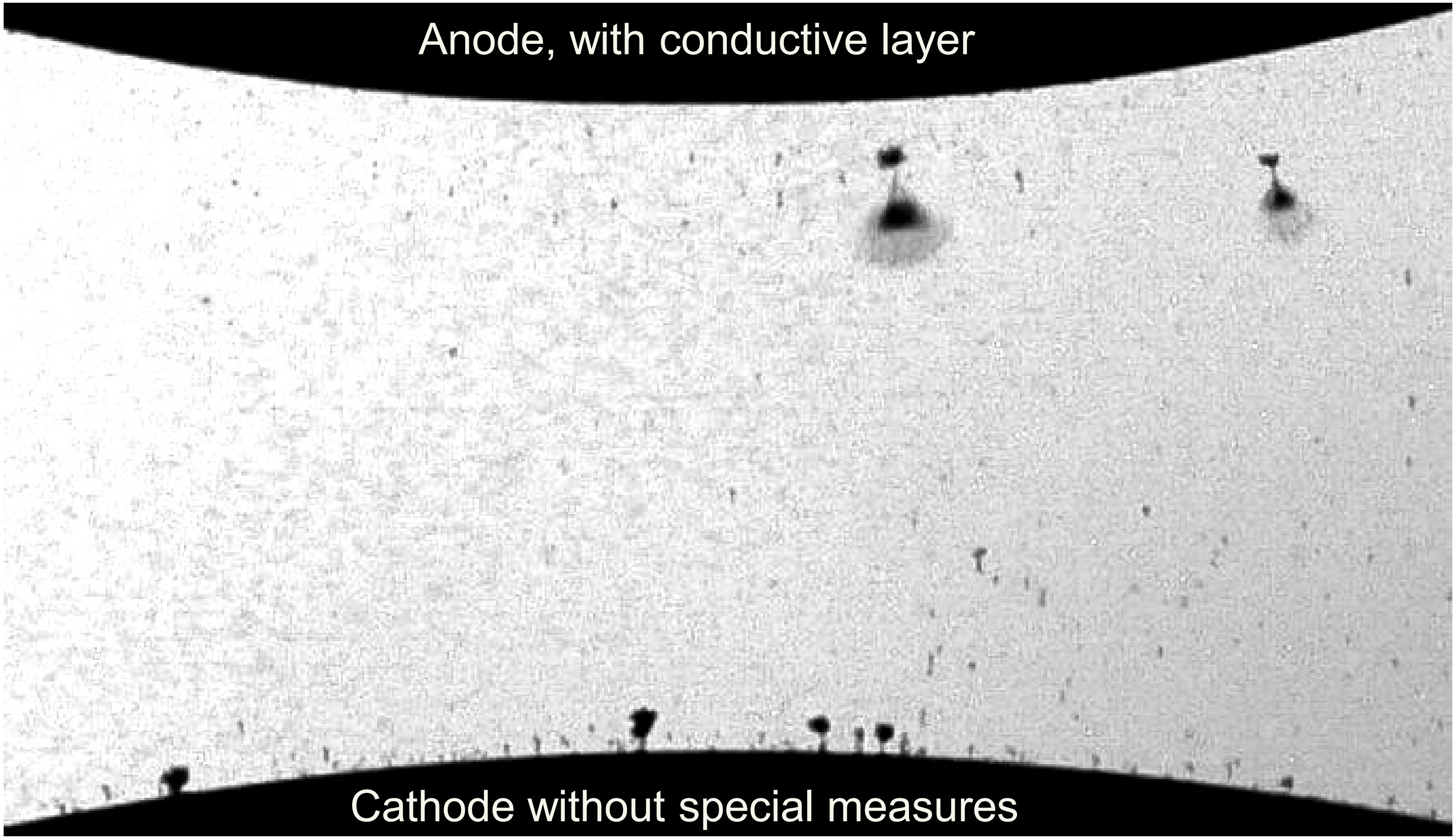
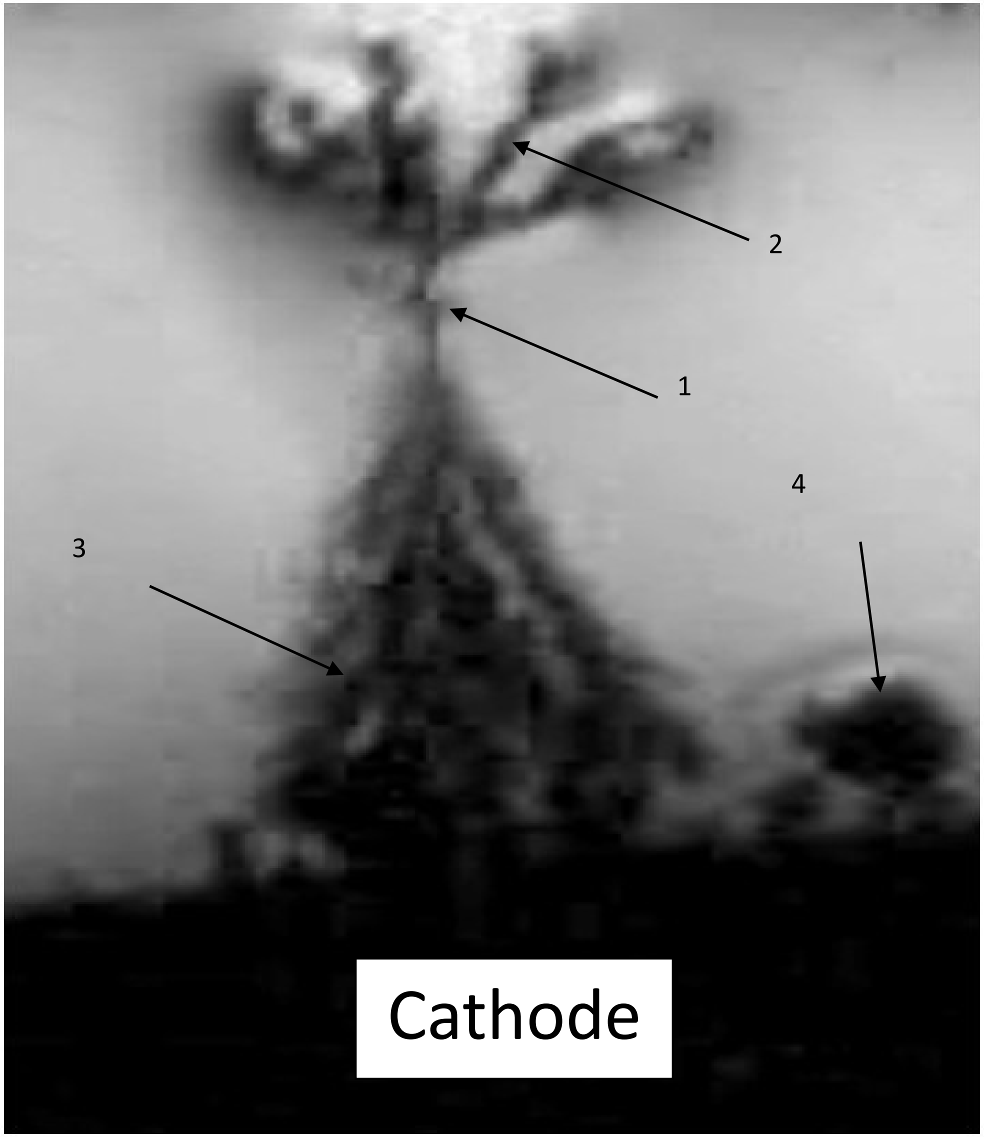
Nonelectrode streamers have another one feature. If they have high conductivity the current both anode and cathode parts should be equal! This mean that current (and movement of one streamer) defines the movement of second streamer!

As for as streamers velocity, one could see that shapes of “semi-streamers” are identical to shapes of usual streamers. The velocity of anode “semi-streamer” is supersomic and two-four times higher than velocity of cathode “semistreamer” that have subsonic value.

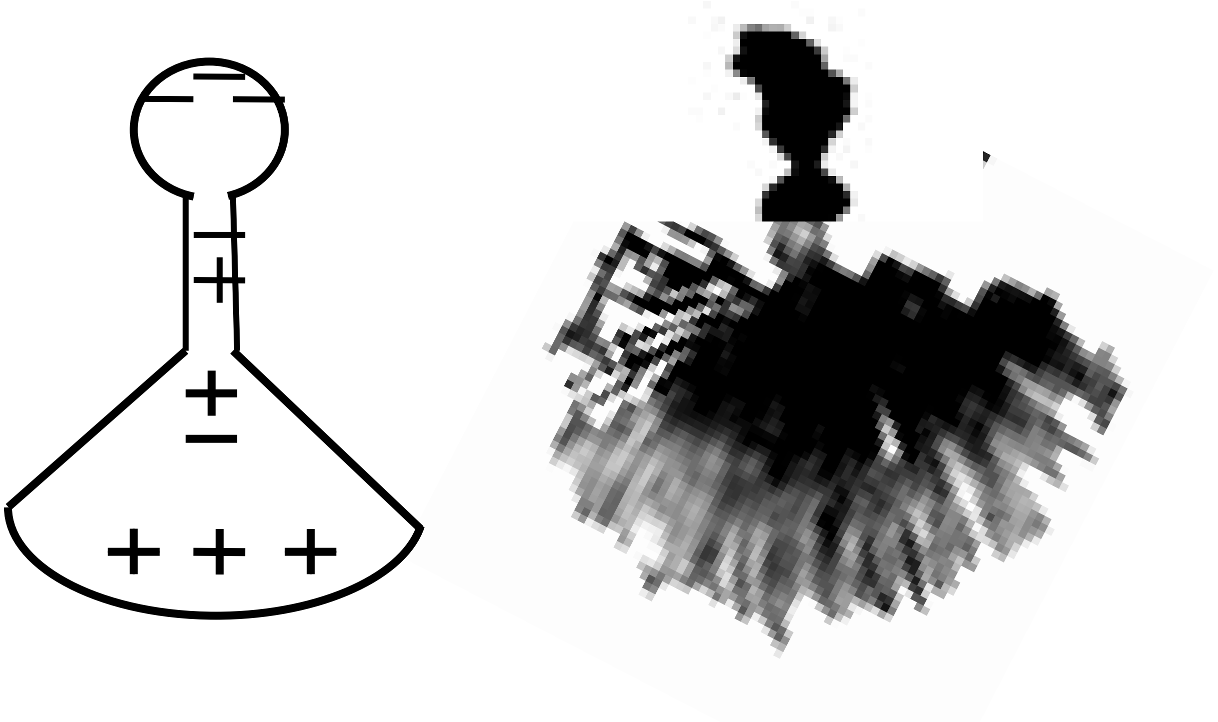
Nonelectrode streamers





Fragment of nonelectrode pair of streamers. The moment of cathode touch of anode part of streamer (3).

Comparison of shapes of nonelectrode streamer and usual cathode and anode streamers



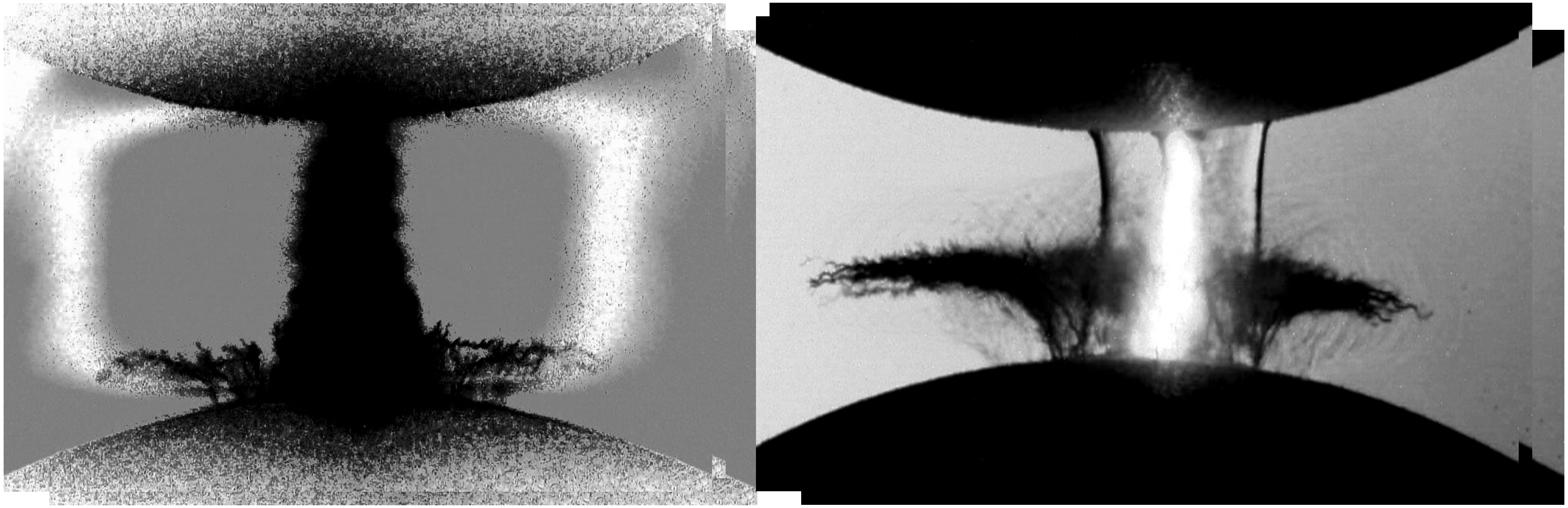
Left: nonelectrode streamer. Right: usual anode and cathode streamers (composition from slides 3 and 4)

As for as microscopic field near branches it could be estimated taking into account the number of branches and it’s radius.

Microscopic field strength at the tip of cathode streamer approximately equals 10 MV/cm.

As for as anode streamer it is a uncertainty. More realistic seems the next: anode streamer has not high conductivity. And microscopic electric field close to tip of branch is less than 10 MV/cm. Estimations from experiments with point electrodes give 5 MV/cm approximately.

As for as kerrogram and shadow image of postbreadown streamers…



Here is horizontal structures like anode usual anode initiated streamers. It develops through zone of negative space charge. The positive space charge is close to anode. Why we can’t register them? They have subsonic velocity like usual cathode streamer and situated inside shock wave. That is why we can’t see it.

What is the mechanism of postbreakdown streamer appearance?

The first reason is conductive layers near electrodes. Voltage action leads to space charge appearance inside the layers. Near anode the positive space charge appears, near cathode – negative space charge. After breakdown these space charge couldn’t simultaneously disappear.

After an “instantaneous” short-circuit of interelectrode gap due to a breakdown the layer charge remains during the time t_m and the distribution of electric field strength in the gap does not vanish but changes fundamentally.

The main feature is generation of radial electric fields.
The evaluation of the radial electrical field strength E_r from the discharge channel with the radius r can be roughly calculated :

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

For U/d ≈ 500 kV/cm and l ≈ 0.1cm, the potential with respect to the electrode is roundly 25 kV. The radial field strength for a conductive channel with the radius r ≈ 0.05 mm is estimated by several megavolts per cm, i.e. exceeds the prebreakdown strength of the field U/d.

It is the reason of postbreakdown streamers!

Conclusion

- 1. Conductive layers near electrodes leads not only to pulse electrical strength increase but to new effects.
- 2. Electrohydrodynamic model of cathode streamer is proposed.
- 3. Nonelectrode streamers spread both to cathode and anode simultaneously as usual anode and cathode streamers. The shapes and velocities are identical to shapes and velocities of usual streamers.
- 4. After interelectrode breakdown the space charges provoke to electric field redistribution. Extra strong radial fields close to primary channel lead to supersonic streamers appearance near cathode and subsonic streamers near anode.

- 5. Computer simulation of Kerr fringes perform to estimate electric field. Macroscopic field near cathode streamer estimated as ≈ 2 MV/cm, so macroscopic field near anode streamer could be estimated less than 400 kV/cm.
- 6. Macroscopic **breakdown field close to electrode** is 400-450 kV/cm both with conductive layers and without layers.

Streamer field estimations

Here one should to mention that electric fields of cathode and anode semistreamers depends one from the other. Anode semistreamer has shape of cone with the angle of ≈ π/2 and cathode semistreamer has form of sphere.

The visible surface area of cathode streamer is 6 times less than the surface area of anode streamer. That is why the **macroscopic field strength of cathode streamer is more than 6 times exceeds macroscopic field of anode streamer**.

Macroscopic field near cathode streamer estimated as ≈ 2 MV/cm, so macroscopic field near anode streamer could be estimated as ≈ 300 kV/cm.

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