Visualisation of plasma induced processes in interelectrode gap of micropinch installation using laser illuminator on molecular nitrogen

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Abstract. The paper presents the results of researched processes in the interelectrode gap of High-current low-inductance vacuum spark (HLIV) on the "PION" system [1] by means of active laser diagnostics with visualisation of radiation field. The influence of the cathode geometry and position of the trigger system on the plasma dynamics of HLIV is considered. The regularities of the discharge for different initial conditions are established. The conditions under which the most stable plasma point is formed in space and time are determined.

1. Introduction
Micropinch discharge (MPD) is usually known as pulsed discharge with a high aspect ratio, which forms a short-lived plasma in very small volume with high temperature and density ($N_e \geq 10^{20} \text{ cm}^{-3}$, $T > 1 \text{ keV}$). One can underline low-inductive vacuum spark (LIVS) among the setups that implement micropinch mode where micropinch is usually known as plasma point. Installations which are based on low inductive vacuum spark (LIVS) are used for a set of applied research and technical tasks as sources of electromagnetic radiation microwave, infrared, visible, ultraviolet and x-ray ranges; as well as powerful plasma flows [2]. Micropinch discharge is a source of vacuum ultraviolet and soft x-ray radiation and is promising for the purposes of X-ray [3], the creation of lasers, X-ray range [4] etc; development of effective sources of multiply charged ions for nuclear physics experiment in terms of technical applications [5]. As the features of installations based on LIVS one can notice the simplicity of the design, the ability to work in frequency mode, the long life time, low cost, and that the physical processes occurring in various $Z$ - pinch discharges, have a lot in common.

In the study of the dynamics of micropinch discharge from the moment of its initiation to the stage of pinching and collapse inside entire section of the discharge gap, it requires application of a set of diagnostic tools, allowing to diagnose the plasma in a wide range of parameters. Methods of diagnostics are easier and more logical to try in small installations, for example, LIVS at relatively low values of the stored energy (0.5 - 10 kJ). At the same time an important thing is the absence of contact with the plasma, so optical diagnostic techniques as passive - based on registration of intrinsic luminosity of plasma and active - on the basis of laser sensing have significant sense.

This paper is the research of micropinch using laser on molecular nitrogen.
2. Experimental setup and results

The work was performed at the "PION" installation with such type of a plasma source as high-current low-inductive vacuum spark (HLIVS). Main parameters are the follows: stored energy is up to 2 kJ and period of discharge is 5.6 ms. Appearance of the installation is presented in figure 1. Electrodes of «PION» installation are the cathode of various shape and peak anode with diameter \( D = 3 \) mm (figure2). Material of the electrodes is Fe (Steel №45, purity 97%, polished). Distance between electrodes during the experiment varied from 3 to 9 mm. Voltage on the main capacitor battery (capacity \( C = 12 \) \( \mu F \)) was up to 20 kV, the pressure in the chamber was equal to \( 10^{-6} \) Torr. Probing was performed by a laser pulse through diagnostic quartz windows, assigned from the discharge axis at a distance of 350 mm to prevent ingress of dust products after discharge. Initiation of the discharge was committed by a source of erosive plasma type (the breakdown on surface of ceramic insulator). One of the Thepler methods [6] was used to investigate the influence of shape of the electrodes on the plasma dynamics of LIVS, and LGI-21 laser on molecular nitrogen was applied as illuminator.

The experimental scheme is shown in Figure 3a. Light beam expander was assembled on base of lenses \( L_1 \) and \( L_2 \) to increase the laser beam diameter from 3 to 12 mm. Mirror \( M_1 \) reflects part of the laser radiation and redirects it to the PEC (coaxial photocell) to determine the exact moment of laser operation. Optical system consisting of two quartz lens \( L_3 \) (\( f = 1 \) m) and \( L_4 \) (\( f = 0.25 \) m) and three interference mirrors with a reflection coefficient 99.99\% on the laser wavelength and located at 45° \( M_2, M_3 \) and \( M_4 \) were used to make an optically conjugated image of the electrode gap on a matrix camera with magnification \( M = 2 \). Application of this scheme allowed removing the camera at a distance of about 6 m from the discharge, which significantly reduced the ambient light from the plasma and reduced the influence of electromagnetic interference on the recording apparatus. In front of the camera pinhole with orifice of 300 microns and an interference filter on the wavelength \( \lambda = 337 \) nm with a bandwidth of 6 nm have been located. Image Registration was implemented on a camera Canon EOS 1000D with removed UV filters and objective lenses in front of the matrix. Micropinch formation was recorded by the current waveform obtained from the Rogowski coil, and a flash of X-rays, registered using the pin-diode (figure 8). So the synchronization between the discharge pulse and laser pulse was established via delay of the pulse generator GZI-21 between the input signal of Rogowski coil and the output signal for laser probe beam (figure3b).
Figure 3. (a) Scheme of experiment on «PION» installation, (b) Synchronization between the discharge pulse and the laser pulse. Red – GZI-21 and green – pulsed generator G5-15 that launches laser probing. Voltage is given in p.u.

Research was conducted for the three electrode systems, differing from each other by shape of the cathode (figure 4): (a) a cylinder with diameter 22 mm; (b) a cylinder of diameter 22 mm with orifice of 3 mm along an axis; (c) a cone with a base of 10 mm diameter and an opening angle of 90°. Bar of 3 mm diameter with spike was used as anode in all cases. Trigger was located on the side of the electrodes (Model presumes that total voltage of the battery is applied instantly in the electrodes and in

Figure 4. Variants of electrode systems used on the "Pion" setup. Colour – electric field lines. Red – maximum. Lines are equipotential lines of field.
the same time when trigger pulse occurs; simulating has been done in Comsol Multiphysics). For each configuration evolution of micropinch has been obtained using experimental shadows. Each separate shadow corresponds to one separate discharge, so it required big statistics.

After submitting of high-voltage pulse to the trigger electrode system, breakdown occurs on the dielectric surface (we observed it just on oscillograms by the delay between signals of discharge and trigger requiring for production of plasma) and auxiliary plasma extends to the electrode gap and initiates vacuum breakdown of the basic discharge. Formed as a result of the breakdown electrons are accelerated by an electric field towards the anode. So plasma cloud near the anode surface is formed, and it starts moving towards the cathode (figure 5). In the first case we see it happens in more late moment – 400 ns where 0 ns is time when X-ray pulse happens (So time was negative if the laser pulse occurred before X-ray, conversely – positive). Probably it was because concentration of auxiliary plasma was high and it was difficult to turn it apart.

![Figure 5. Plasma formation near the anode at initiation of vacuum breakdown.](image)

Moving toward the cathode, anode plasma cloud begins to shrink to the discharge axis by magnetic forces of the discharge current, leading to the formation of the sausage-type instability. Depending on the shape of the electrodes necking may be offset from the axis of the discharge gap, or placed on its axis. In the figure 4 modeling of electrical potential and lines of electric field at initial conditions are presented. It was noticed that in the first and second cases we have more significant changes of field and so we could expect that there is the dependence discharge formation on localization of trigger here. Obtained shadows confirm that assumption for this case of flat cathode (figure 6).

![Figure 6. Curving of plasma channel towards the side where trigger has been located, t = 0.1 µs](image)

After necking, according to the theory of radiative collapse [7] in terms of Pease-Braginskii condition (discharge current must exceed a critical value of the current - 50 kA for iron), the plasma point (PP) is formed. When using a cylindrical cathode without orifice (figure 7a) the following
features were observed: in a new system of electrodes (up to 120 shots) only one PP formed at time ~ 800 ns (60%) with scatter of 150 ns or ~ 1100 (~ 25%) with 100 ns; while amount of discharges increases, x-ray radiation moment shifts to 850 ns from the beginning of the current flow, and the dispersion increased to 300 ns. Localization region in the space is constricted of ~ 0.4 × 1 mm² and displaced towards the trigger at distance 1 mm approximately. Two plasma points (figure 8) were formed unlikely (less than ~ 15%), probably because of bridging currents of peripheral plasma. Herewith, time between peaks is between 10 and 50 ns.

New electrodes

Wasted electrodes

Figure 7. Dispersion of X-ray emission time and its probability (that matches amplitude in the figure) for three electrode systems (red rectangular bar): (a) - cathode without orifice, (b) - cathode with orifice, (c) - conical cathode. Red single pulse on all figures corresponds to X-ray emission in the beginning of the discharge evolution. Green – discharge current.

Figure 8. Waveform with double X-ray pulse for the cases with flat cathode. Red – X-ray, Blue – laser, Green – Discharge current. On the left - cathode without an orifice, on the right - cathode with an orifice.

In the case of a cathode with an orifice (figure 7b) moment of X-ray emission also was changed while number of shots increases, but the origin of the change was different: after installing new electrodes (up to 120 shots) one PP mainly formed at time ~ 950 ± 80 ns (~ 80%); then it was more likely to occur in later times, and after about 200 discharges micropinch formed mainly in time 1100 ± 60 ns from the beginning of the current flow. Localization region in the space is constricted by ~ 0.6 × 1 mm², and displaced towards the trigger. Dual X-ray peaks were detected more often and time interval between two stages of maximum compression was more significant than in the first case when cathode without orifice is used (150 - 200 ns).

Using the conical cathode (figure 7c) plasma point formed in moment of time 800 ns (~ 80%) or about 1100 ns (~ 15%) or about 1300 ns (~ 5%) with a dispersion of no more than ~ 80 ns. When wasted electrodes were investigated, probability of later moments was reduced to zero. After 200 shots
micropinch preferably was formed at the time of 800 ns from the start of current flow. In this case, the spatial domain of preferential formation of instability (size ~ 0.4 × 0.4 mm²) located symmetrically relative to the axis of the discharge gap.

3. Conclusion
The experimental results appear to try to explain physical processes, occurring in the interelectrode gap of micropinch installation. Using the method of a laser probing information about the dynamics of LIVS plasma for three different electrode configurations has been obtained experimentally. Such system of registration with digital camera is very convenient and one can obtain good quality of shadows spending short time. The most significant influence on the localization of the hot point was observed in the case of a flat cathode, so the region is shifted relative to the system axis. Hereby, in the case of conical electrodes the spatial domain is located symmetrically relative to the axis of the discharge gap in smaller volume and formation of PP is more stable.

While amount of discharges increases moment of x-ray radiation shifts in all cases but behavior of this displacement has different character. The dependence the time interval between the formations of two PP on the configuration of the electrode system also can verify different origin so the electrode system has significant role in micropinch processes.

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