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PLASMA DYNAMICS

# Influence of the Current Growth Rate on the Polarity Effect in a Wire Array in the Angara-5-1 Facility

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**Abstract**—It is shown that, at a sufficiently high current growth rate, the initial stage of implosion of a wire array is significantly affected by the radial electric fields. Due to the specific electrode configuration of wire arrays, the magnitude of the oppositely directed radial electric fields in different wire segments can reach 5 MV/cm. It is found that the process of plasma formation proceeds in different ways in segments with oppositely directed initial radial electric fields. The influence of this effect (the so-called "polarity effect") on the implosion of cylindrical tungsten wire arrays in the Angara-5-1 facility becomes significant when the load voltage grows at a sufficiently high rate.

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## 1. INTRODUCTION

In recent years, the implosion of cylindrical micron-wire arrays (liners) under the action of nanosecond megaampere current pulses has received much attention [1–4]. An important line of research in this field is investigation of the initial stage of breakdown—the so-called "wire initiation" [5]. An increase in the wire temperature at the front of the current pulse leads to the evaporation of light impurities from the wire surface. The breakdown of a thin gas layer produced near the wire surface results in the formation of a plasma [4–13]. After the current is switched from the wire to the formed plasma, the power deposited in the wire decreases significantly. The further expansion of the wire material after breakdown is determined by the energy deposited in the wire before breakdown [9, 11, 14]. It was shown in [11] that the energy deposited in the wire before breakdown increases with increasing growth rate of the current flowing through the wire.

The parameters and dynamics of the plasma formed due to the breakdown of the gas layer depend on the direction of the radial electric field at the wire surface before breakdown—the so-called "polarity effect." At a certain electrode configuration of a wire array, the radial electric field can exceed the axial electric field by a factor of 10–100. Sarkisov et al. [10] showed that the breakdown of the ambient gas occurs several nanoseconds earlier when the radial electric field is negative, i.e., when it pulls electrons out of the wire, thereby causing electron emission. The emitted electrons cause an early breakdown of the thin surface gas layer and, accordingly, considerably reduce the energy deposited in the dense core of the exploding wire. When the radial electric field is positive, it hampers electron emission from the wire. In this case, the surface gas layer is broken down later and, therefore, the energy deposited in the wire is higher than in the previous case. Thus, it was found in [15] that, when a wire was placed in a metal tube biased negatively with respect to the wire, both the breakdown time and the energy deposited in the wire increased considerably. The experiments carried out in the MAGPIE facility [16] showed that the rate of plasma formation on the surfaces of aluminum wires and, accordingly, the instant at which the plasma begins to move toward the array axis depend on the direction of the radial electric field before breakdown.

In experiments on the implosion of tungsten wire arrays in the Angara-5-1 facility, the polarity effect manifested itself only when the growth rate of the load voltage was high enough [5]. To increase the voltage growth rate in the stage of wire initiation, it is necessary that the prepulse be suppressed completely, which requires designing a special prepulse switch.

Most high-power generators have a prepulse. For pulses with a duration of about 100 ns, the prepulse duration is ~1 μs and the prepulse amplitude is about 1–10% of the amplitude of the main pulse. As a rule, the prepulse is an undesirable phenomenon, because it can lead to plasma formation before the main pulse and can even destroy the load.

In the Angara-5-1 facility, the prepulse was suppressed with the help of eight prepulse switches mounted in each of the eight water transmission lines. As a result, the prepulse amplitude was reduced to lower than 10 kV (~1% of the main pulse amplitude). Nevertheless, in experiments with wire arrays, the plasma was observed to form before the beginning of the main pulse.

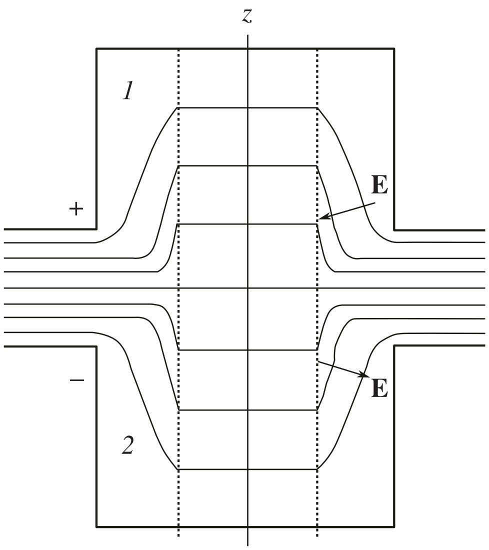


**Fig. 1.** Sketch of a wire array with electrodes. The heavy solid lines show the electrodes, the dashed lines show the wire array, and the light lines show the equipotential surfaces. Here, **E** is the electric field vector and the numerals *1* and *2* indicate the anode and cathode cavities, respectively. The wire array and the electrodes are axisymmetric with respect to the *z* axis.

To further reduce the prepulse amplitude, we designed and tested an additional surface-breakdown switch. The switch was placed at the center of the liner unit. The wire array was insulated from the high-voltage electrode (cathode) by a dielectric disk. The length of the switch gap along the insulator surface was 1–2 mm. Test experiments showed that the switch efficiently suppressed the prepulse. The prepulse voltage at the wires was about 10 V (~0.001% of the main pulse amplitude). In this case, a 1-μs prepulse can heat tungsten wires by no more than 10 K.

An increase in the switch gap length to 10 mm allowed us not only to decrease the prepulse amplitude but also to increase the voltage growth rate at the wire array before the wire initiation. The 10-mm-long switch gap was broken down at a voltage of ~100 kV. In this case, the plasmas formed at the wires near the anode and the cathode expanded at different rates. The plasma expansion rate near the cathode (where the positive radial electric field hampered electron emission from the wire) was higher than that near the anode (where the negative radial electric field pulled electrons out of the wire).

In experiments on the implosion of cylindrical tungsten wire arrays in the Angara-5-1 facility, the electrode configuration provided the generation of oppositely directed radial electric fields of up to 4000 kV/cm at different segments of the wires with an initial diameter of 6 μm. In this configuration, the polarity effect became significant only when the voltage growth rate was increased substantially by applying a prepulse switch with a wide discharge gap.

On May 18, 2007 (after this article was accepted for publication), it was reported in [17] that shortening the prepulse in the Zebra facility with the help of the same kind of switch led to an increase in the soft X-ray yield.

## 2. EXPERIMENTAL SETUP

In the experiments carried out in the Angara-5-1 facility [18], we used simple wire arrays with diameters of 12 and 20 mm. The total number of tungsten wires in an array was 20–40, the wire diameter being 6–8 μm. The working chamber was evacuated by oil-vapor pumps.

To produce a radial electric field at the wires, it is necessary that there be electrodes near the wire surface. In order for the radial electric field to be directed toward (from) the wire, the anode (cathode) should be set close to the wire surface. Hence, placing the ends of the wire array in the cavities made in the anode and cathode (see Fig. 1) results in the generation of oppositely directed radial electric fields near the anode and cathode before breakdown. In the anode and cathode cavities, the radial electric fields are directed toward and from the wire, respectively.

A schematic of the liner unit is shown in Fig. 2a. To produce the radial electric field, the ends of the wire array were placed in the cavities made in the anode and cathode. Before breakdown, the radial electric field in the anode cavity is directed toward the wire and that in the cathode cavity is directed from the wire. The radial field $E$ at the external surface of the wires before breakdown is plotted in Fig. 2b as a function of the height $h$ (here, the ordinate is matched to the schematic of the liner unit shown in Fig. 2a). It can be seen that the normal component of the electric field at the external surface of the wires reaches its maximum value (4000 kV/cm) at the ends of the cavities (at the ordinates +6 and –6 mm). Outside the cavities, the field varies almost linearly and vanishes at the point with the zero ordinate.

In order to increase the voltage growth rate at the wires, a prepulse switch was mounted at the cathode in series with the array. The conical dielectric surface along which breakdown occurs is shown by the heavy line in Fig. 2.

The length of the switch gap along the insulator surface was varied from 1 to 10 mm. A similar switch with a 1-mm-long gap was previously used to suppress the prepulse [7].

The current time derivative $J'$ was measured with magnetic probes installed at a radius of 55 mm. It was assumed that the current flowing through a circle of this radius was equal to the total current in the wire array.

It should be noted that, in our experiments, the voltage at the wire array was not measured. We measured only the voltage $U$ between the anode and the cathode at a radius of 6 cm by using an inductive divider [19]. Estimates show that the growth rate of the electric field

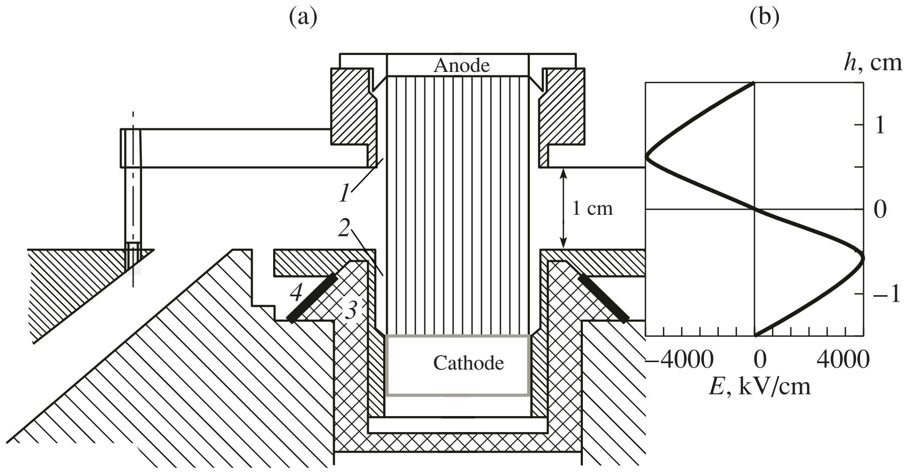


**Fig. 2.** (a) Schematic of the liner unit: (*1*) anode cavity, (*2*) cathode cavity, (*3*) dielectric, and (*4*) conical surface along which breakdown occurs (heavy solid line); (b) radial electric field $E$ at the wire before breakdown as a function of the height $h$ (here, the ordinate is matched to Fig. 2a).

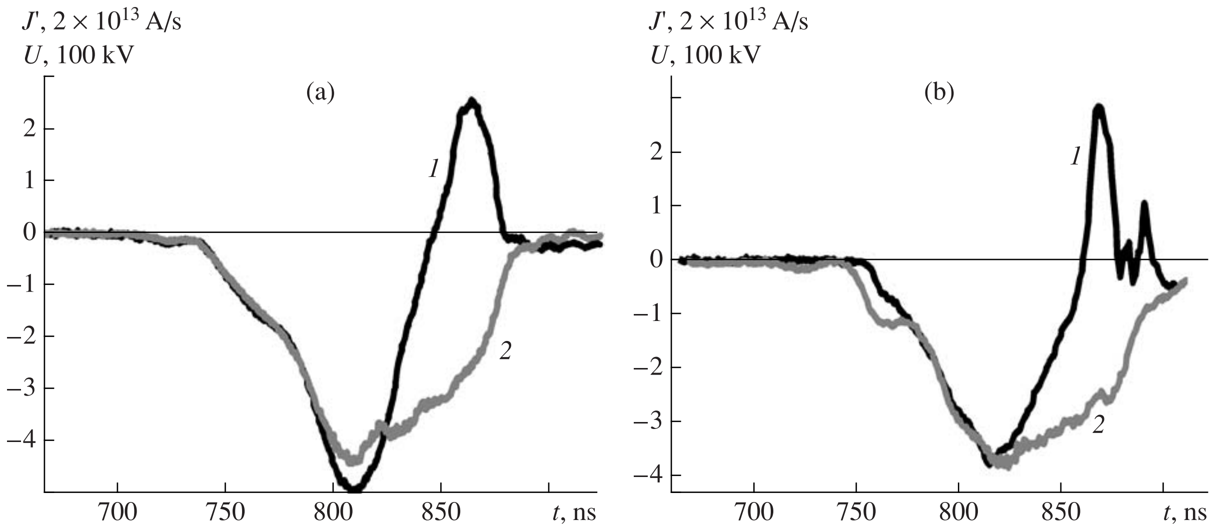


**Fig. 3.** Waveforms of the (*1*) current time derivative $J'$ and (*2*) voltage $U$ in experiments carried out (a) without a prepulse switch and (b) with a 10-mm-gap switch.

strength at the wires was $10^{12}$ V/(cm s). An increase in the current growth rate should result in a proportional increase in the voltage growth rate at the wire array. Therefore, the term "current growth rate" is used here as an equivalent of the term "voltage growth rate at the wire array."

The images of an imploding wire array were obtained with the help of frame laser shadowgraphy and a frame X-ray image tube.

## 3. EXPERIMENTAL RESULTS

### *3.1. Switch Operation*

Figure 3 shows synchronized waveforms of the current time derivative and voltage. Hereafter, the time scale is such that the voltage at the liner unit begins to grow at ~740 ns. Without a prepulse switch, the signals of the current time derivative and voltage between 725 and 760 ns were similar in shape. This means that the current grows synchronously with the voltage. In the presence of a switch, the voltage within this time interval is nonzero, while the current derivative is zero, i.e., no current flows through the wire array. At a switch gap length of 10 mm, the gap is broken down at a voltage of ~100 kV. In order to describe the process of the rapid switch operation, it is necessary to analyze not only the first but also the second time derivative of the current.

Figure 4 shows the time dependences of the voltage $U$ at the liner unit; the current growth rate $J'$; and the second time derivative of the current, $J''$. It can be seen that the switch gap is broken down at the time 760 ns. During the first three nanoseconds, the current growth

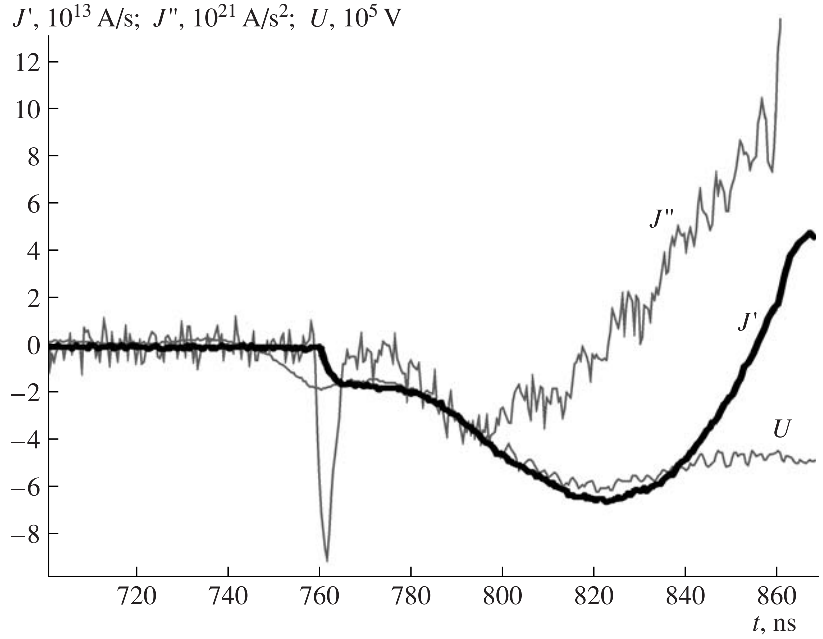


**Fig. 4.** Time dependences of the liner voltage $U$, current growth rate $J'$, and second time derivative of the current $J''$.

rate $J'$ increases to $(1.0–1.5) \times 10^{13}$ A/s. For the Angara-5-1 experiments, this value can be considered moderate, because, at the time 820 ns, the current growth rate $J'$ reaches $6.5 \times 10^{13}$ A/s. The instant of breakdown, the energy deposited in the wire, and the further wire dynamics depend on the current growth rate. The total number of wires in the array was 60; therefore, during the first three nanoseconds, the current growth rate in a single 6-μm wire was about 200 A/ns. (Note that, in [9], the current growth rate during the electric explosion of a single 16-μm tungsten wire was 170 A/ns.) As will be shown below, not only the current growth rate itself but also the rate at which it increases within this time interval substantially affect the breakdown of the gas layer formed at the wire surface. The narrow spike in the second time derivative of the current at the time 764 ns corresponds to the breakdown of the switch gap. The second time derivative of the current at this instant is equal to $(0.9–1.0) \times 10^{22}$ A/s$^2$, which is two to three times larger than typical values achieved in the Angara-5-1 facility in the stage of the growth of the current time derivative (see the time interval 760–820 ns in Fig. 4).

### *3.2. Polarity Effect*

Figure 5 shows three successive shadow images of a wire array. The synchronized waveforms of various parameters in this shot are shown in Fig. 6.

In each image, the anode and cathode regions of the wire array are seen to differ significantly from one another. In the lower parts of the images (near the cathode), the wires are seen to be substantially expanded, whereas in the upper parts, the expansion is smaller. Thus, in the middle image, the size of the shadow image near the cathode is 0.66 mm, while near the anode, it is 0.2 mm. The corresponding plasma expansion velocities estimated from the shadow images are 30 and 8 km/s, respectively. Note that these velocities are much higher than the average expansion velocity (0.1 km/s) of the dense core of a tungsten wire in an imploding wire array, measured by probing with 5-keV X rays at 70 ns after the beginning of the discharge.

Thus, both the breakdown of the gas layer formed at the wire surface and the further plasma expansion depend substantially on the specific features of the current growth rate during the several first nanoseconds.

Without a prepulse switch, no polarity effect was observed. With a long switch gap (up to 10 mm), the voltage growth rate at the array increased substantially. It is clearly seen in the laser shadow images of a wire array that, in this case, the plasma corona near the cathode (where the radial electric field hampers electron emission from the wire) is wider than that near the anode (where the radial electric field pulls electrons out of the wire). Thus, both the design of the liner unit and the voltage growth rate at the wire array influence the wire breakdown and the polarity effect. An increase in the voltage growth rate at the wires in discharges performed with a long switch gap results in a pronounced polarity effect.

Note that different wires behave in different ways; i.e., the polarity effect manifests itself only on some wires.

Figure 7 presents enlarged shadow images of the same wire in the array shown in Fig. 5. From Fig. 7a, which shows the wire image taken before the shot, one

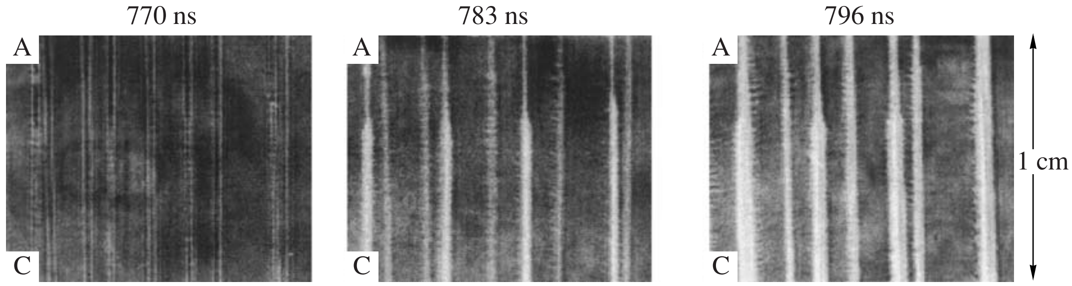


**Fig. 5.** Shadow images of a wire array, taken at different instants in the initial stage of a discharge: A is the anode, and C is the cathode.

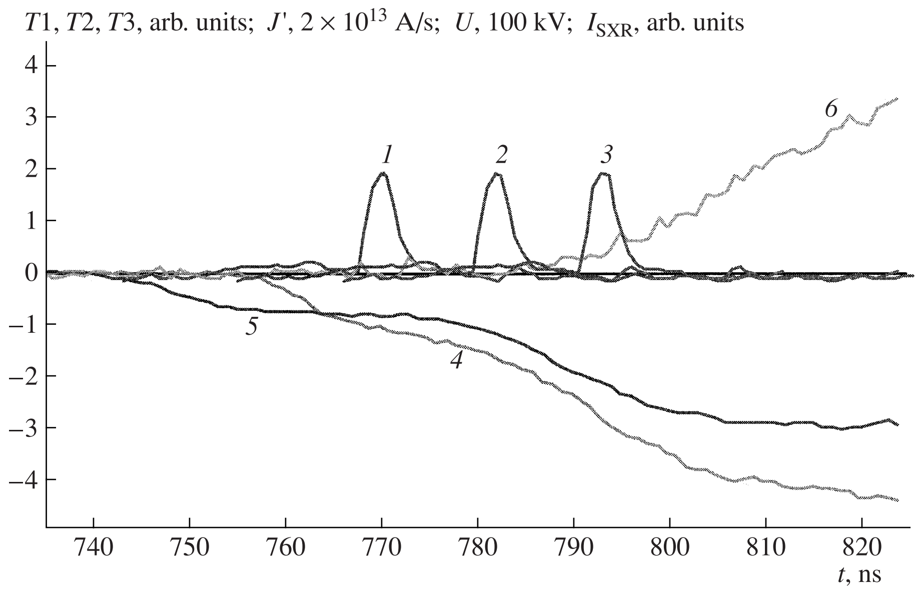


**Fig. 6.** Synchronized waveforms of the (*1–3*) laser pulses *T*1, *T*2, and *T*3, used to obtain the shadow images presented in Fig. 5; (*4*) current time derivative *J*'; (*5*) voltage *U* at a radius of 6 cm; and (*6*) soft X-ray intensity $I_{SXR}$.

can determine the spatial resolution of laser probing. In this shot, it was about 50 μm. The images presented in Figs.7b–7d were taken at the successive instants indicated in Figs. 5 and 6.

It should be noted that the image presented in Fig. 7b and those presented in Figs. 7c and 7d were produced under somewhat different conditions.

The image in Fig. 7b was produced by the rays refracted in the plasma. Some of the refracted rays went beyond the input aperture of the recording system. The diffraction pattern recorded on the film presents a superposition of the refracted rays. The intense exposure of the axial region of the image by probing rays indicates that laser radiation is weakly absorbed by the plasma.

The images in Figs. 7c and 7d were produced by the probing rays (including those refracted in the plasma), which were considerably absorbed by the plasma. Some of the refracted beams could also go beyond the input aperture of the recording system.

It is clearly seen in Fig. 7b that the diameter of the dark axial region in the cathode part of the wire is about 1.5 times smaller than that in the anode part. This indicates that, at the instant corresponding to Fig. 7b, the plasma diameter near the cathode is smaller than that near the anode. This means that the plasma near the cathode was produced later than near the anode.

In Figs. 7c and 7d, the situation is opposite. The light axial region corresponds to strong absorption of the probing rays in the plasma. Now, the plasma diameter near the cathode is larger than that near the anode. This means that, although the plasma near the cathode was produced later, by the instants corresponding to Figs. 7c and 7d, it expanded more strongly. This is because, near the cathode, the breakdown occurred later and, accordingly, the energy deposited in the cathode part of the wire was larger than that deposited in the anode part. Therefore, the plasma expansion rate in the cathode region is higher than in the anode region. It should be emphasized again that the dense wire core

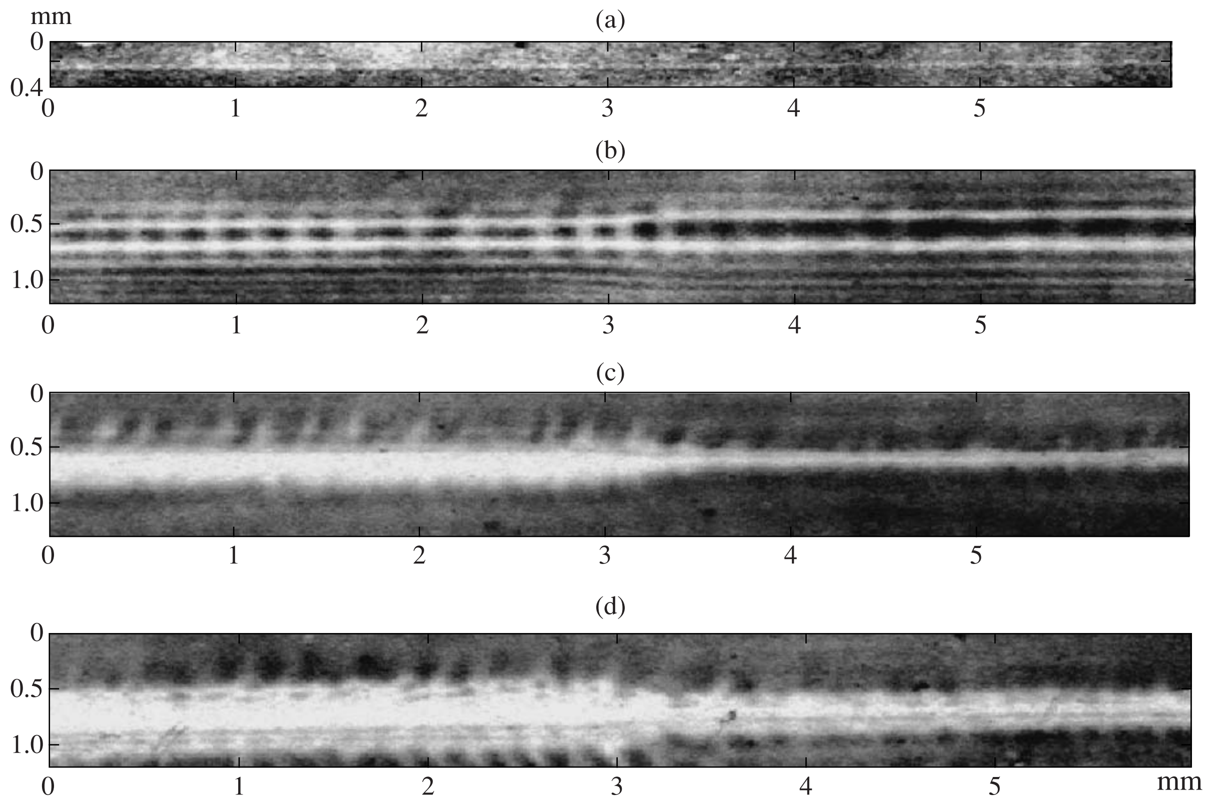


**Fig. 7.** Enlarged shadow images (negative) of the same wire in the array shown in Fig. 5. The cathode is on the left, and the anode is on the right. Image (a) was taken before the shot, and images (b)–(d) were taken at the successive instants indicated in Figs. 5 and 6.

expands at a rate that is two orders of magnitude lower than the plasma expansion rate.

## 4. DISCUSSION

Thus, the experiments on the implosion of cylindrical tungsten wire arrays in the Angara-5-1 facility have demonstrated the influence of the current growth rate on the polarity effect. The polarity effect becomes appreciable only when the current growth rate at the beginning of the process is sufficiently high. In order to observe the polarity effect, it is necessary that not only the current growth rate be high [11] but also that the high current growth rate be reached before breakdown, i.e., that the second time derivative of the current be large at the very beginning of the discharge. The larger the current time derivative before breakdown, the higher the current itself and, accordingly, the larger the energy deposited in the wire before breakdown.

The polarity effect depends on the amount of energy deposited in different segments of the wire before breakdown. Since in our experiments, the current was constant along the wire, different values of the energy deposited in the wire segments with different directions of the radial electric field were related to different breakdown times.

The polarity effect is determined by the competition between the two processes: the current growth and the breakdown of the gas layer near the wire surface. The use of a prepulse discharge switch allows one to increase the second time derivative of the current; as a result, the energy deposited in the wire before breakdown increases. In our experiments, applying such a switch increased the second time derivative of the current by a factor of 2–3. Therefore, for the same breakdown time and a given polarity, the energy deposited in the wire before breakdown should increase by a factor of 4–9. It can be, however, that, in this case, the breakdown time will decrease. Then, the increase in the deposited energy will be somewhat smaller and the polarity effect will be less pronounced. Thus, the polarity effect depends on the specific features of the current growth during the several first nanoseconds.

It should be noted that the length of the intermediate region between the strongly and weakly expanded parts of the same wire is about 0.5 mm (see Fig. 5).

It can be seen from Fig. 2 that, in the 1-cm-long central region, the normal component of the electric field at the external side of the wires varies almost linearly from –4000 to 4000 kV/cm. However, the transition between the strongly and weakly expanded parts of the wire occurs over a narrow region of length 0.5 mm. In this region, the normal component of the electric field at the external side of the wires changes its sign. Over the 0.5-mm-long region, the normal component of the electric field at the external side of the wires changes by about 400 kV/cm. This is quite sufficient for the field emission. When the sign of the normal component of the electric field is such that it pulls electrons out of the wire, the field emission [10] can accelerate the breakdown of the gas layer near the wire surface. The earlier the breakdown, the less the energy deposited in the wire before breakdown. When the sign of the normal component of the electric field is opposite, there is no field emission.

In all the images presented in Figs. 7b–7d, it is clearly seen that the formed plasma is inhomogeneous along the wire axis. In the cathode part of the wire, the inhomogeneity period is 200–300 μm, while in the anode part, this period is appreciably longer and the inhomogeneity itself is less pronounced. Such an inhomogeneity is probably related to the internal structure of the wire, which is produced by drawing through a wire die.

The wire breakdown and the polarity effect can also be influenced by the quality of the wire–electrode contact. In particular, depositing the electrode surface with a thin layer of a vacuum compound at the sites of contact can result in a considerable increase in both the breakdown time and the energy deposited in the wire [20]. Different resistances of the wire–electrode contacts can lead to different delays of the current growth in the wires; as a result, the polarity effect at some wires can be absent (see Fig. 5).

The character of wire breakdown can also be affected by oil vapor, because, as was noted above, the vacuum chamber in the Angara-5-1 facility was evacuated by oil-vapor pumps.

## 5. CONCLUSIONS

The experiments carried out in the Angara-5-1 facility have shown that the character of the implosion of a tungsten wire array depends on both the sign of the radial electric field at the wire surface (the polarity effect) and the current growth rate. To observe the polarity effect in the Angara-5-1 facility, it is necessary that not only the current growth rate be high but also that the second time derivative of the current at the beginning of the process be sufficiently large (up to $10^{22}$ A/c$^2$). An increase in the second time derivative of the current was achieved by installing a prepulse discharge switch near the wire array.

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