Comparison between a hydrogen - filled gap breakdown and a breakdown along exploding tungsten fine wire

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Experimental results on the hydrogen - filled gap breakdown are discussed. The hydrogen pressure was varied within the range from 3.6 to 736 torr. The electric field strength across the gas-filled gap was varied within the range from 5 to 30 kV/cm. The rise time of a voltage pulse applied to the gap was 10 ns. Parameters of the hydrogen - filled gap breakdown were compared with the breakdown along of a fine wire during its electric explosion in vacuum. The problem of how the wire diameter, the rate of energy deposition in the wire influence on the wire explosion and the accompanying breakdown was investigated experimentally. The wire explosion was performed both at a positive and at negative polarity of the high-voltage electrode. A current density growth rate of 6.10^{11}–5.10^{16}A/(s cm^2) was achieved. It was shown that the breakdown along a wire is similar to the gas breakdown in many respects.

1. Introduction

Although a lot of research works concerning nanosecond wire electrical explosions have been carried out, an interest in such investigations, which is determined both by the fundamental character of the phenomenon and its possible applications, still remains. One of such applications is imploding tungsten wire arrays used as a high power source of soft X-ray radiation [1-6]. Wire array optimization is associated with simulation both of the wire array implosion process and the electrical explosion of a separate wire. MHD modeling of the wire electrical explosion is performed taking into account the tungsten wire conductivity value.

One of the factors inhibiting the increase in the deposited energy to values sufficient for the wire sublimation is an early breakdown of the interelectrode gap along the wire surface and the subsequent switching of the current from the wire to the conducting medium surrounding the wire. In [7], it was shown that the shunting breakdown is caused by the gas desorption from the wire surface. In this case, the breakdown of the interelectrode gap along the desorbed gas shunts the wire, thereby impeding the increase in the deposited energy to values sufficient for its complete evaporation. The energy deposited in the wire material can be limited by the specific properties of the gas breakdown and by the influence of other factors inhibiting or promoting breakdown of the gas desorbed from the wire surface.

The aim of this study is to investigate the mechanism for the development of the shunting breakdown along an exploding wire and to find common characteristics of breakdown along the wire and in a gas medium. We performed a number of experiments on the breakdown of a hydrogen - filled gap under different pressures. As well we carried out experiments on the explosion of fine tungsten wires in vacuum. In these experiments, we studied how the wire diameter, the rate of energy deposition in the wire influence the wire explosion and the accompanying breakdown. The assumption of the thermal expansion of the desorbed gas allowed us to represent the experimental data on the breakdown along a wire in different operating regimes as a dependence on the similarity parameters E_{br}/n and $n\cdot\tau_{br}$ (where n [cm^{-3}] is gas densities, E_{br} [V/cm] is electrical field strength, $\cdot\tau_{br}$ [sec] is instant of breakdown) i.e., in a form conventionally used in gas-discharge physics.

2. Experiment

2.1. Experimental facility and diagnostics

The RLC generator described in [8] was used in the experiments. The equivalent circuit of the generator is given in Fig. 1. A high-voltage electrode had both positive and negative polarity relative to the return current posts. The use of the different polarity of high voltage electrode is connected with the experimental fact that breakdown along a wire occurs later in case of the positive polarity in

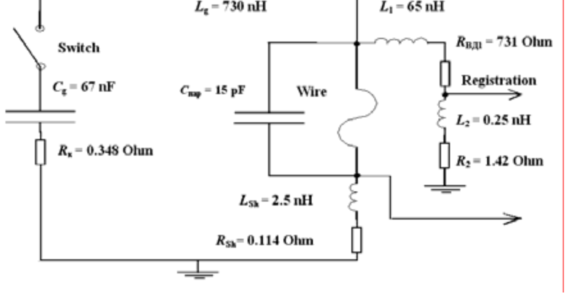

Fig. 1. Electric circuit of the RLC generator.

comparison with the negatively charged high-voltage electrode [9,10].

In our experiments, we used the following electrical diagnostics: an active high-resistance divider, an B-dot located on the side of the high-voltage electrode, and a shunt located on the side of the ground electrode.

2.2. Experiments on the explosion of tungsten wires

We used 6.35- and 30.48-μm tungsten wires with a length of 20 ± 0.5 mm in the experiments on the wire explosion. The charging voltage U_0 of the capacitor was 20 kV. The circuit inductance L_g was 730 nH; in this case, the circuit resistance R_c (not including the resistance of the shunt and wire) was 0.234 Ohm. The circuit capacitance C_g was 66.9 nF. We used a gas spark gap as a switch. The load unit was installed in the working chamber of the generator (Fig. 2). As return current posts, we used six 1-cm-diameter rods equally spaced round a circle 10 cm in diameter. The return current posts were chosen such that the stray capacitance of the load unit was minimal. All the components of the chamber were made of nonmagnetic materials. In all the experiments, the vacuum chamber was pumped-out by an oil-free pump to a residual pressure of (3 ÷ 5) 10^{-5} torr.

Test experiments on wire explosions showed that,

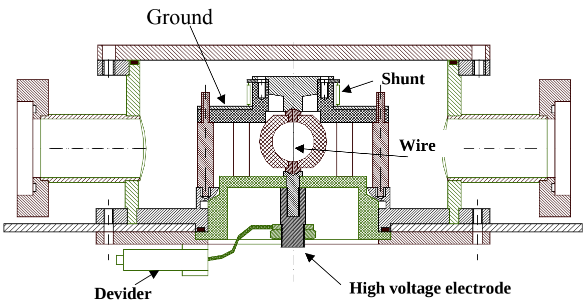

Fig. 2. Schematic of the vacuum chamber with the fine wire load.

when the contacts of the electrodes with a wire were not quite good, the gap voltage could change abruptly at the beginning of the current pulse; such changes were practically impossible to take into account. Moreover, a plasma was produced at the site where the wire contacted the electrode; this could substantially influence the processes of wire heating and electric breakdown along the wire. To exclude the influence of contacts on the results of experiments, the wire was mounted in a special caprolan holder (Fig. 2) and the wire contacts with the electrodes were soldered. As a result, a reliable contact of the electrodes with the wire was ensured. After soldering, the holder was washed with water and ethanol.

2.3. Experiments on the breakdown of a gas-filled gap

To compare the parameters of breakdown along a wire to those of the breakdown of a gas-filled gap, we performed a series of test experiments. In these experiments, we studied the breakdown of a gap filled with hydrogen at different pressures. The holder with the wire was replaced with 3-cm-diameter plane electrodes, the interelectrode gap length being equal to 6 mm (Fig. 3). When the generator was switched on, a voltage pulse with a rise time of 10 ns and amplitude of 18 kV was

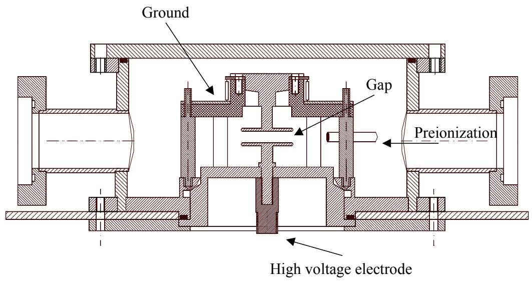

Fig. 3. Schematic of the vacuum chamber with the gas-filled gap load.

applied to the gap. We measured the time interval from the beginning of the voltage pulse to the instant of breakdown and the gap voltage at this instant for different gas pressures within the range from 3.6 to 736 torr. The measurements were performed in two regimes: with and without UV preionization. As a source of UV radiation, we used a spark discharge along a dielectric surface. The UV source was located in the middle of the gap at a distance of 5.5 cm from the symmetry axis of the system. The period of current oscillations in the circuit of the UV source was 6 μs. The time interval between the beginning of the preionization pulse and the instant at which the generator was switched on was 1.5 μs.

3. Results and discussion

3.2. Explosion of wires in vacuum

As the wire is heated by the current flowing through it, the adsorbed gas begins to be evolved from the wire surface. When the wire temperature reaches about 1100°C, almost all the gas is desorbed from the wire surface and a thin dense gas layer is produced around the wire [11]. In [7], it was suggested that it is this desorbed gas that plays a key role in the breakdown along the wire.

In [11], it was shown that the surface density of hydrogen atoms adsorbed by a tungsten surface is in the order of 10^{15} cm^{-2}; moreover, there are also such elements as nitrogen, carbon, and oxygen on this surface. Since hydrogen is the lightest element, it is this gas that should determine the boundary of the gas layer. The number of hydrogen atoms adsorbed by the surface of a tungsten wire with a diameter d_w and length l_w is:

$$N_0 \approx 10^{15} \cdot \pi \cdot d_w \cdot l_w .$$

The process of the gas desorption can be described as [12]:

$$-\frac{dN}{dt} = C_1 \cdot N^2 \cdot e^{-\frac{C_2}{R \cdot T_w}}$$

where N [atoms/cm^2] is the number of desorbed H atoms, $C_1 = 5 \cdot 10^{-3}$ [$cm^2 \cdot s^{-1}$], $C_2 = 3.1 \cdot 10^4$ [J], T_w [K] is the wire temperature.

The expansion velocity of the gas shell depends on the gas temperature (Fig.4). In our simulation we will assume that the temperature $T(t)$ of the gas portion desorbed at the moment t is equal to the wire temperature, which can be estimated as:

$$T_w(t) = (m_w \cdot C_W(T_w(t)))^{-1} \cdot \int I(t) \cdot U(t) \cdot dt,$$

where m_w is the wire mass and C_W $(T(t))$ is the tungsten heat capacity [14, 15]. Then, the kinetic energy of desorbed atoms was averaged.

To describe a desorbed gas distribution we used a model of a shock wave described in [13]:

$$n = n_0 \cdot \left(1 - \frac{(r-R)^2}{R^2}\right)^{\alpha} ; \quad \alpha = \frac{3-\gamma}{2 \cdot (\gamma - 1)}; \quad R = U_{\max w} \cdot t;$$

$$U_{\mathrm{maxw}} = \sqrt{\frac{2 \cdot k \cdot T_g}{m_H}}$$

where R is the gas shell radius, γ is the adiabatic exponent, T_g is the desorbed gas temperature in °K, m_H is the hydrogen atomic mass, U_{maxw} is the most probable velocity of Maxwellian distribution.

Using the measured values of the breakdown voltage U_{br} and the time interval between the time at which the generator is switched on and the instant of breakdown τ_{br}, we can plot the reduced electric field E_{br}/n as a function of the parameter $n \cdot \tau_{br}$. The resulting functional dependence of E_{br}/n on $n \cdot \tau_{br}$ will allow us to compare the parameters of breakdown along a wire in vacuum to those of gas breakdown.

3.2. Breakdown of a Gas-Filled Gap

We carried out experiments with air-filled gap breakdown in order to be sure in the accuracy of our measurements. We studied breakdown in air at different gas densities n with the method described in [16, 17]. Since similar measurements were carried out by another author it was possible to compare our data with the data given in Ref.16. The comparison is given in fig.5. As follows from the Fig. 4, our measurements and date taken from [16] are in a good agreement.

Figure 6 shows the results of experiments on the breakdown in hydrogen with and without UV

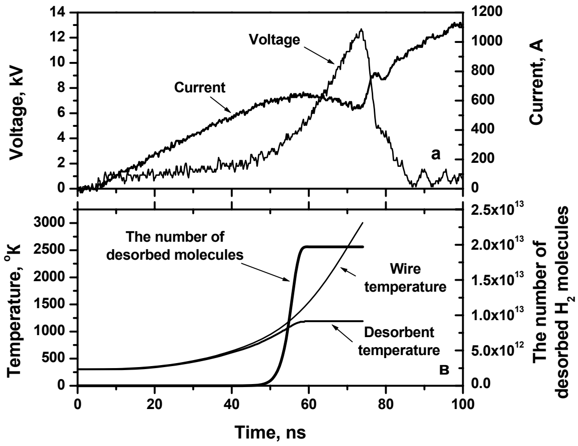

Fig.4 a- current and voltage oscillograms, b – estimation of the wire temperature, desorbed gas temperature and number of desorbed H atoms.

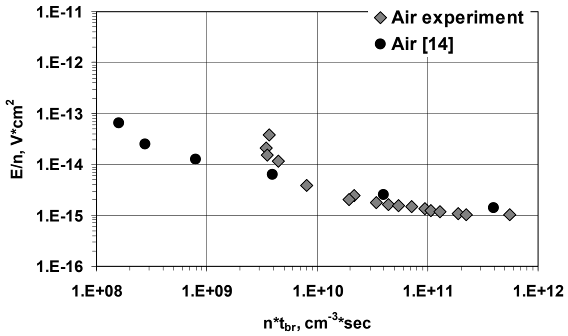

Fig.5. Dependence of the parameter E_{br}/n on $n \cdot \tau_{br}$. observed in experiments on the breakdown of the gap filled with air.

preionization. As it was expected, the curve $E_{br}/n = f(n \cdot \tau_{br})$ in the absence of UV preionization lies somewhat higher than that in the presence of preionization, and it is somewhat different in shape. The squares and rhombuses in Fig. 6 presents the data obtained during the explosion of tungsten wires in vacuum. The parameters E_{br} and $\cdot \tau_{br}$. were found experimentally and the density of the desorbed gas n was calculated by the method described in Section 3.1.

The above experimental dependence can be fitted by the function:

$$E_{br}/n = \alpha \cdot (n \cdot \tau_{br})^{\beta} .$$

for breakdown in hydrogen (without UV preionization), the coefficients are: $\alpha = 5.6 \cdot 10^{-4}$, $\beta = -1.0274$.

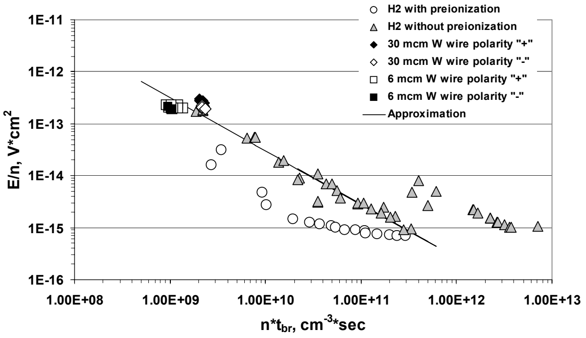

Fig. 6. Dependence of the parameter E_{br}/n on $n \cdot \tau_{br}$. observed in experiments on the breakdown of a gap filled with hydrogen with and without UV preionization and in experiments on the electric explosion of a 6.35-μm and 30.48-μm tungsten wire in

A comparison of the curves shown in Fig.6 shows that the parameters of breakdown along a wire are close to those of gas breakdown.

The experimental data on the breakdown of fine tungsten wires make it possible to determine the instant at which simulation of the energy deposited in the wire should be stopped. If the simulation of electric explosion is performed with allowance for the thermal expansion of the desorbed gas, then the instant of breakdown is determined by the last expression.

4. Conclusion

In this paper, we have presented results from the studies of the electric explosion of a fine tungsten wire in vacuum and the shunting breakdown accompanying this explosion.

A comparison of the experimental results on the explosion of tungsten wires in vacuum with the results of test experiments on the breakdown of a gas-filled gap has shown that the breakdown along a wire is similar in many respects to the gas breakdown. A method has been proposed that takes into account the thermal expansion of the desorbed gas and makes it possible to quite exactly determine the instant at which the shunting breakdown along a wire occurs.

5. Acknowledgments

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6. References

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