“Research of Switched Power by Nitrogen Diode Switches in the Subnanosecond Time Range”

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The study of the switched power by nitrogen diode switches in the subnanosecond time range depending on the pressure was carried out. The discharge gap was made in the form of a break in the central electrode of a 50-Ohm coaxial gas-filled line. In the experiments, a stainless steel cathode and anode with a tip radius of 1 cm were used. Such a large radius of rounding of the electrodes was chosen to form a uniform electric field in the discharge gap, which facilitated the interpretation of the obtained experimental data. A subnanosecond pulse with amplitude of 100 kV with a front of 250 ps (at the level of 0.1-0.9 in amplitude) was applied to the discharge gap. The gap breakdown occurs at the front of the applied voltage pulse. To measure the voltage pulses, the method of reflectometry was used: the pulse voltages at the output of the pulse generator (PG) and reflected from the tested gas gap were recorded using wide-band capacitive voltage dividers built into the transmitting coaxial line connecting the PG and the discharge gap. Waveforms of the voltage at the gap when it is broken and in the absence of a breakdown (idle mode) were obtained. The method of conducting of such experiments is described in details in [1-4]. We have previously shown [5] that the discharge under these conditions develops with the participation of runaway electrons, which significantly reduce the overvoltage of the discharge gap and the pulse breakdown voltage [1-3].

A fixed-length discharge gap was used, and the nitrogen pressure gradually increased from 5 atm to 40 atm during the experiment. Using the method described in [6], the oscillograms of the current flowing through the discharge gap were restored for all experimental points. Important parameters of any switch are coefficient of efficiency and the residual resistance after switching. To determine the coefficient of efficiency, it is necessary to know the pulse energy passed through the spark gap and the energy stored in the line connecting the spark gap and the PG. To determine these values, we used the voltage and current waveforms we obtained. As a result, the coefficient of efficiency dependences on the nitrogen pressure were obtained.

REFERENCES

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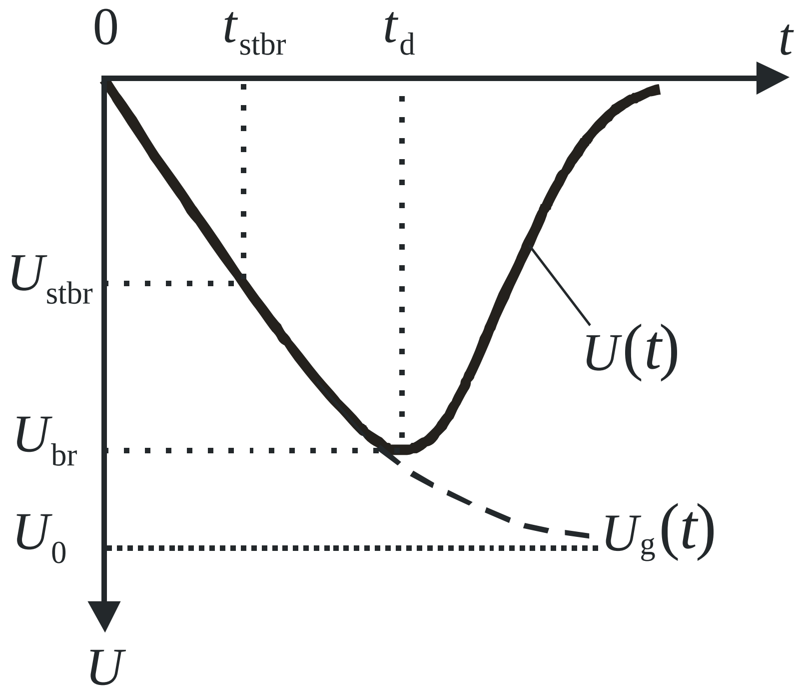
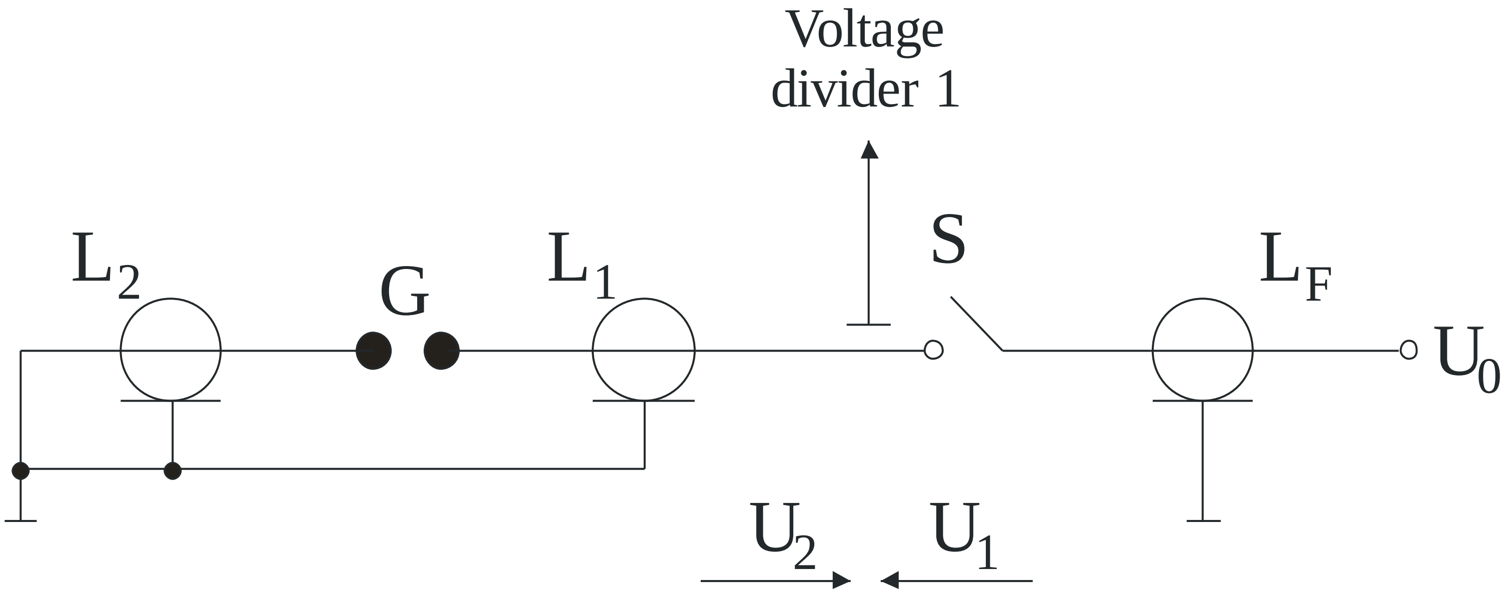
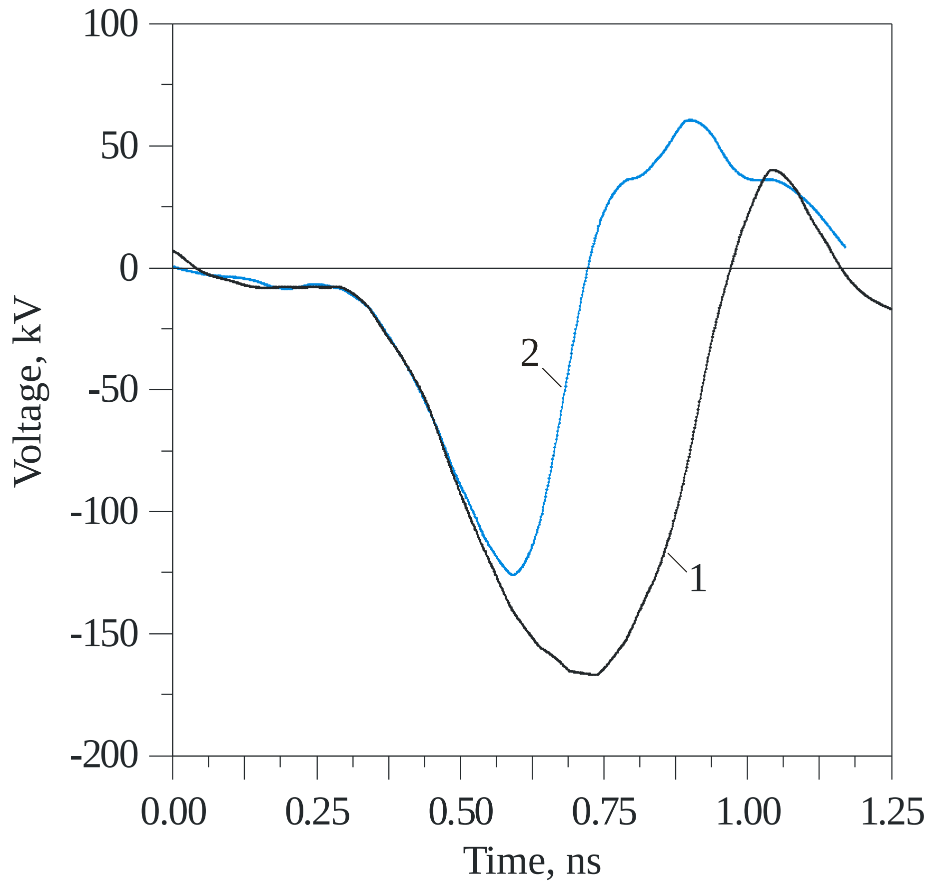


$U(t)$ – voltage at the discharge gap G in the prebreakdown stage and in the stage of breakdown. Ug(t) – front of the voltage pulse applied to the gas discharge gap; U_0 – double amplitude of the voltage pulse applied to the discharge gap; U_{stbr} – static breakdown voltage; t_d – breakdown delay time ($t_d = t_{st} + t_{form}$, where t_{st} – statistical delay time; t_{form} – breakdown formation time); t_{stbr} – the time for which the voltage across the discharge gap reaches the level of the static breakdown voltage. The current I(t) in the circuit is determined by $I(t)=(U_g(t) - U(t))/z$, where z is the equivalent impedance of the coaxial lines.



The equivalent circuit of discharge circuit. L_F – pulse generator (PG) forming line; S – key; L_1 – 50-Ω coaxial transmission line; L_2 – 50-Ω load coaxial transmission line with grounded end; G – a gas discharge gap formed as a break in the central electrode of a coaxial line; U_0 – the charging voltage of the PG; U_1 – the incident voltage wave $U_g(t)$; U_2 – voltage across the discharge gap at the breakdown delay and the breakdown stages $U(t)$.



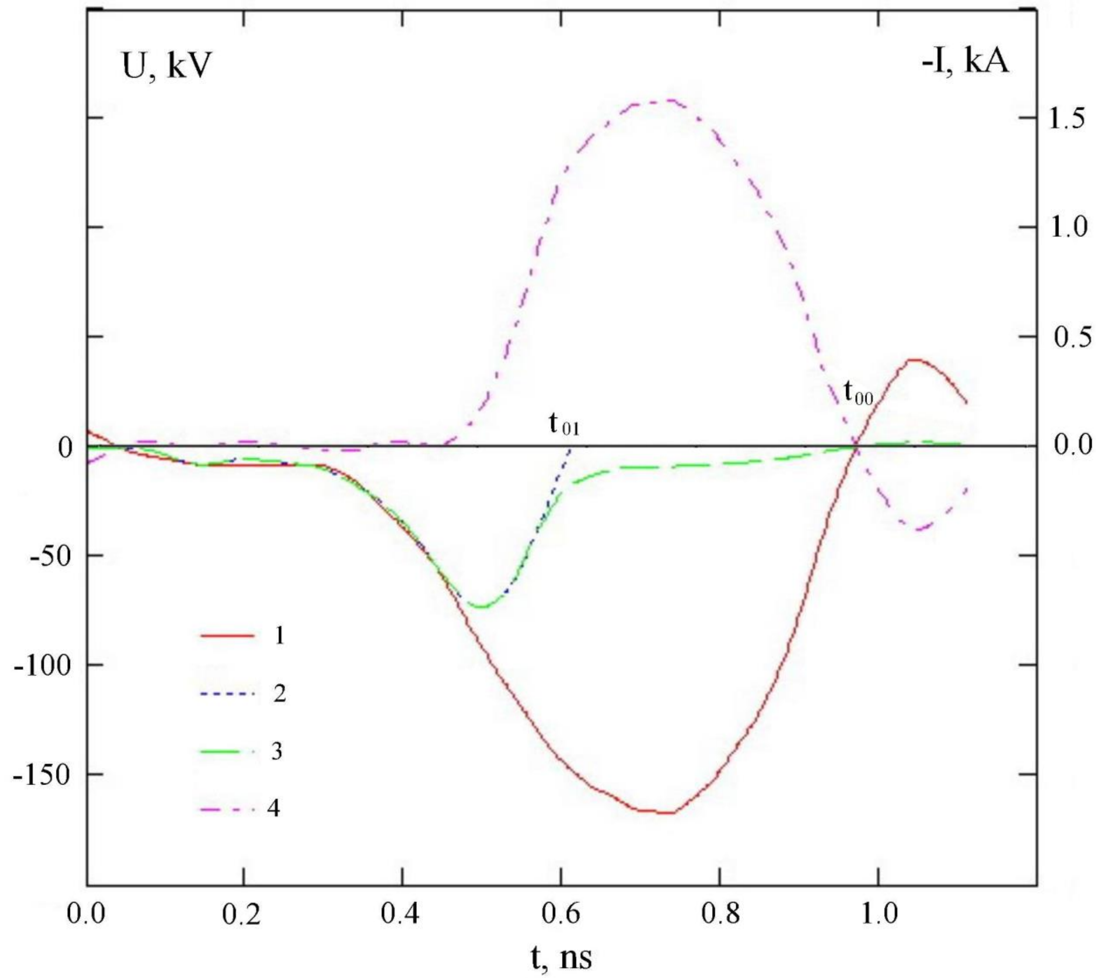
Waveform 1 – voltage at the discharge gap *G* in the case of breakdown absent (in idle mode) $U_g(t)$. Waveform 2 – voltage at the discharge gap *G* in the prebreakdown stage and in the stage of breakdown (nitrogen pressure was 40 atm, discharge gap length d = 0.5mm) $U(t)$. The amplitude of the reflected pulse takes into account the voltage doubling at the gap in the prebreakdown stage. The non-zero inductance of the capacitive voltage divider causes a positive voltage spike at the back front of the pulse, which is a problem in measurements in the subnanosecond range.

To approximate the final section of the voltage waveform at the discharge gap, the dynamics of changes in the ionization frequency during the voltage drop was analyzed. It is known that the ionization frequency strongly depends on the electric field strength (at a fixed pressure). When the voltage drops to the level of $0.2 \div 0.3 * U_{br}$ (U_{br} – breakdown voltage in pulse mode) the characteristic ionization time $\tau_i = 1/\nu_i$ (ν_i is the ionization frequency) becomes longer than the duration of the voltage pulse applied to the discharge gap. In this case, the concentration of electrons in the plasma can be considered quasi-constant and, consequently, the resistance of the gas-discharge plasma can also be considered unchanged (let's denote it as R_p). To ensure the smoothness of the solution (continuity of the first derivative) at $t \geq \tau_1$, we introduced a transient resistance function in the form:

$$R(t) = (R_1 - R_p) * \exp(-(t - \tau_1)/(2 * (\tau_2 - \tau_1))) + R_p$$

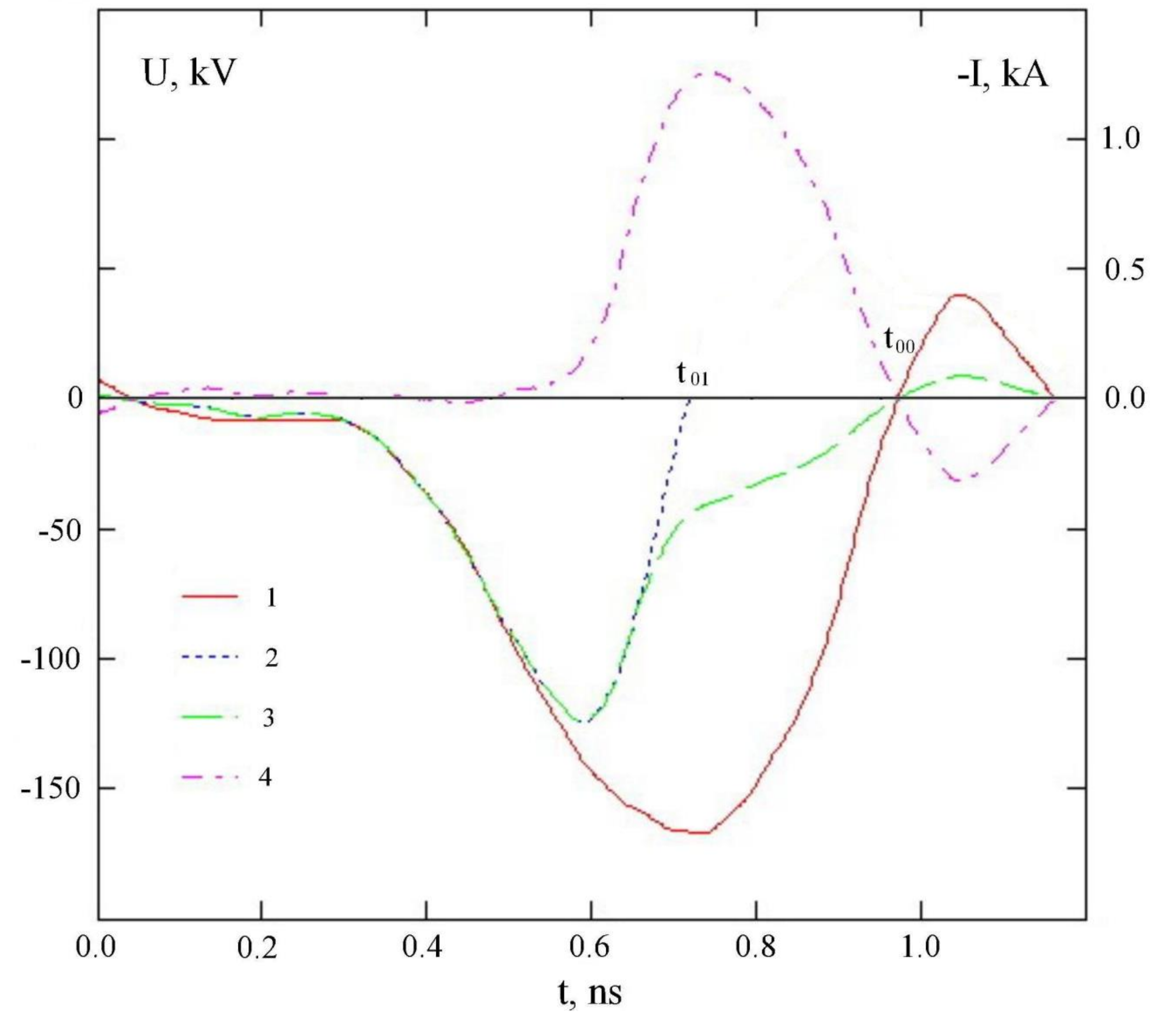
where: τ_1 is the moment of time when the voltage on the back front of the voltage waveform $U = 0.5 * U_{br}$, and the plasma resistance at this moment is equal to R_1;
τ_2 is the moment of time when the resistance of the plasma becomes equal to R_p;
The resistances R_1 and R_p are calculated as a quotient of U/I, where I is calculated using the method described in slide 3

Thus, at $t \geq \tau_1$, the discharge gap can be replaced by the resistance R(t).



1. The voltage pulse applied to the gas discharge gap;
2. The voltage at the discharge gap G in the prebreakdown stage and in the stage of breakdown;
3. The voltage at the discharge gap G in the prebreakdown stage and in the stage of breakdown with approximation of the final section of the voltage drop;
4. The current I(t) in the discharge gap.

The discharge gap length d = 0.5 mm. The nitrogen pressure p = 5 atm.



1. The voltage pulse applied to the gas discharge gap;
2. The voltage at the discharge gap G in the prebreakdown stage and in the stage of breakdown;
3. The voltage at the discharge gap G in the prebreakdown stage and in the stage of breakdown with approximation of the final section of the voltage drop;
4. The current I(t) in the discharge gap.

The discharge gap length d = 0.5 mm. The nitrogen pressure p = 40 atm.

Energy of the falling wave: $w = \frac{1}{R}\int_0^{t_{00}} U^2(t)dt = 0.123 J$

The energy deposited in the discharge (provided in the form of heat and light): $w_{1,2} = \int_0^{t_{01,02}} U_{1,2}(t) I(t) dt$

where:
w_1 is the energy obtained from experimental waveforms (see slides 7 and 8). It is clearly understated;
w_2 is the energy obtained from experimental waveforms modified according to our proposed method (see slides 7 and 8);
$U_1(t)$ is experimentally obtained uncorrected oscillogram of the voltage at the discharge gap at the breakdown delay and breakdown stages;
$U_2(t)$ -) is corrected oscillogram of the voltage at the discharge gap at the breakdown delay and breakdown stages;
$I(t)$ – current in the discharge gap;
t_{00}, t_{01}, t_{02} are the times when the waveforms turn to zero, i.e.$U_1(t_{00})=U_1(t_{01})=U_2(t_{02})=0$.

Pressure, atm	w_1, J	w_2, J	I_{max}, kA	U_2, (kV) in maximum current	Resistance of plasma, Ω	Efficiency factor, %
5	$3.2*10^{-3}$	$7.1*10^{-3}$	1.56	8.9	5.6	94.33
10	$5.8*10^{-3}$	$1.2*10^{-2}$	1.88	12.7	6.8	90.25
20	$4.2*10^{-3}$	$1.4*10^{-2}$	1.79	20.9	11.6	88.62
30	$5.4*10^{-3}$	$1.4*10^{-2}$	1.32	34.9	26.4	88.62
40	$6.1*10^{-3}$	$1.4*10^{-2}$	1.26	40.7	28.0	88.62

CONCLUSION

It is shown that the efficiency factor of subnanosecond diode switchs with electrodes providing initially uniform distribution of the electric field and a fixed-length interelectrode gap decreases with increasing gas pressure. At the same time, the efficiency factor remains constant in the pressure range of 20 – 40 atm. According to our works [Ivanov S.N., Lisenkov V.V. Investigation of the Prebreakdown Stage of the Self-Sustained Subnanosecond Discharge in High Pressure Nitrogen // Journal of Applied Physics. – 2018. – Vol. 124. – art. no 103304; Ivanov S.N., Lisenkov V.V. Study of the Formation Time of a Self-Sustained Subnanosecond Discharge at High and Ultrahigh Gas Pressures // Plasma Physics Reports. – 2018. – Vol. 44., № 3. pp. 369-377] in the specified pressure range, the switching characteristics of the discharge are completely determined by runaway electrons, which provide a multi-electron initiation mechanism in the gas volume at a certain stage of the discharge development. A slow gentle section of voltage drop is typical for discharges with multi-electron initiation.