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Optimization of a Nanosecond Pre-Ionization Switch's Breakdown Jitter Characteristic Based on a Probability Distribution Model of Electron Avalanche's Initiation

TIANCHI WANG[1], HAIYANG WANG[2], WEI CHEN[2], AND TAO HUANG[2]
[1]Key Laboratory of Particle & Radiation Imaging, Ministry of Education, Tsinghua University, Beijing 100084, China
[2]State Key Laboratory of Intense Pulsed Radiation Simulation and Effect, Northwest Institute of Nuclear Technology, Xi'an 710024, China
Corresponding authors: Wei Chen (chenwei6802@163.com) and Haiyang Wang (wanghaiyang@nint.ac.cn)

ABSTRACT The breakdown jitter characteristic of a self-triggered pre-ionization switch that works under pulses with the rising time of about one hundred nanoseconds was improved based on the probability distribution model of electron avalanche's initiation. Contrary to what we might imagine, premature pre-ionization nearly brought about no improvement on the breakdown jitter characteristic. To reduce the switch jitter, analysis of the probability distribution model indicated that the generating rate of initial electrons should maintain a high value when the electric field in the gap was high enough to initiate an effective electron avalanche. Experimental results proved that adjusting the breakdown time of the trigger gap or letting the electrons in the arc channel of the trigger gap become a steady source of initial electrons could both reduce the breakdown time delay jitter to 1ns-2ns when the breakdown time was about 95% of the peak time, this means that high energy transfer efficiency and low jitter were realized simultaneously.

INDEX TERMS Gas switch, nanosecond pulse, pre-ionization, self-triggering, time delay jitter.

I. INTRODUCTION

Cascade and parallel systems are commonly utilized to generate high voltage and high current pulses with fast rise time, they have been widely used in Z-pinch drivers and EMP simulator drivers [1]–[4]. These pulsed power systems commonly use Marx generators or pulsed transformers to generate primary pulses with slow rise time, and pulsed switches are used to transfer and steepen the primary pulses [3]. To make sure that multi-channel pulses can be superposed successfully without threatening the insulators, synchronous breakdowns of switches in each stage are important [2]. So the transfer switches are required to work stably under pulse voltage, meanwhile, to obtain a high energy transfer efficiency (and satisfactory waveform on the load under specific circuit structure), the transfer switches should break down near the peak time of input pulse [5]. It brings forward a high request on the jitter characteristics of breakdown time delay. Like the voltage-second characteristic in high voltage engineering [6], increasing *du/dt* can reduce the breakdown time delay and make the switch break down before the peak time. But it doesn't make sense if the efficiency and load waveform quality are sacrificed to get the stability.

A triggered gas switch might obtain high efficiency and high stability simultaneously by creating an overvoltage gap or pre-ionization effect [7]. Trigatron switch and V/N field distortion switch are both electrically triggered, they have a wide working range with operating voltage from dozens of kV to MV level, operating condition from DC to pulse [8]–[10]. V/N switch creates overvoltage gaps to reduce the breakdown jitter. Trigatron switch can reduce the breakdown jitter by creating overvoltage gaps (fast breakdown process) or pre-ionization (slow breakdown process). The breakdown time delay jitter of MV electrically-triggered switches can be reduced to 3ns or below as they work under pulses with the rising time of several hundred nanoseconds [8], [10]. The 6MV laser trigger switch used in ZR composes of a trigger gap and more than 20 cascade overvoltage gaps [11], the trigger gap first breaks down due to the laser pre-ionization, then the overvoltage gaps

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breakdown in sequence, the breakdown time delay jitter of the 6MV switch can be reduced to around 4ns [12]. Considering that the statistical time delay is the dominant part of breakdown time delay in a gas spark switch, the UV lamp can also be utilized to illuminate the cathode and reduce the statistical time delay jitter [13]. However, an external trigger system increases the complexity and cost of the whole generator and lowers its mobility. Hence, the self-triggered switch is a better choice due to its simplicity and low jitter characteristic [5], [14]–[16]. Corona stabilized switch [17] and UV-illumination switch [5], [14] are classed as self-triggered pre-ionization switches. In a self-triggered pre-ionization switch, corona discharge, surface flashover, or spark discharge of another gap are realized without an external trigger signal to create the initial electrons in the main gap. Spark discharge of a trigger gap is a more stable pre-ionization source compared to others, so it is more suitable to be used as the pre-ionization source. Effective pre-ionization requires the initial electrons to occur at the proper time, premature or late pre-ionization might both lead to unsatisfactory results.

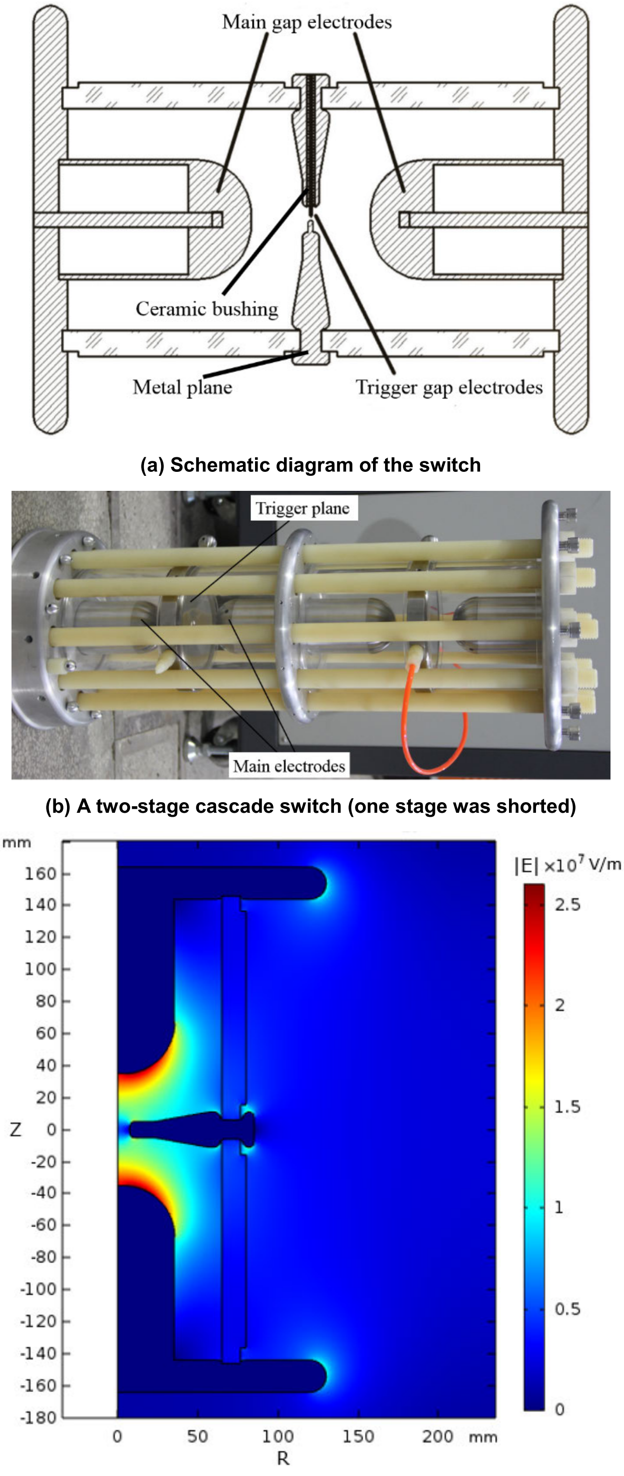
In this paper, a self-triggered pre-ionization transfer switch was tested under both self-breakdown and pre-ionized breakdown mode under pulses with about 100ns rise time. The probability distribution model of effective electron avalanche's initiation was used to qualitatively explain the breakdown jitter characteristics of the pre-ionization switch and propose improvement approaches. Two approaches were adopted and the breakdown time delay jitters of the modified switches were further reduced.

II. EXPERIMENTAL SETUP

A. SWITCH STRUCTURE AND EXPERIMENTAL PLATFORM

Figure 1 demonstrates the pulsed transfer switch with a self-triggered pre-ionization gap. The trigger gap electrodes were fixed on a metal trigger plane in the middle of the switch, one electrode was made of stainless steel and equipotential with the trigger plane, while another electrode was made of tungsten and insulated from the metal plane through a ceramic bushing. The main gap electrodes were both made of stainless steel. The main gap distance was 7cm (actually was 6cm because the thickness of the trigger plane was 1cm) and the trigger gap distance was 1.5mm. Figure 1(c) demonstrates the simulation result of electric distribution in the switch, the electric potential on the cathode, trigger plane, and anode were −1000kV, −500kV, and 0kV, respectively. The maximum norm of electric field strength was 262.8kV/cm, the average norm of electric field strength was 166.7kV/cm (1000kV/6cm), so the enhanced field factor was about 1.6 (262.8/166.7).

Figure 2 is the equivalent circuit of the voltage division structure of the switch. C_1, C, and C_2 are the structural capacitance between the main gap cathode and the trigger gap cathode, the trigger gap cathode and anode, the trigger gap anode and the main gap anode, respectively. R_1, R, and R_2 are the paralleled voltage division resistors of the three gaps. Due to the coaxial configuration of tungsten trigger electrode and ceramic bushing, C is approximately 15pF, while C_1 and C_2 are about 1 pF, much smaller than C, and R_1, R_2 are much smaller than the capacitive reactance of C_1, C_2. When the equivalent frequency of the input pulse is f, the voltage division ratio between the main gap and the trigger



(a) Schematic diagram of the switch

(b) A two-stage cascade switch (one stage was shorted)

(c) Distribution of the electric field's norm in the switch

FIGURE 1. Structure of the switch [15].

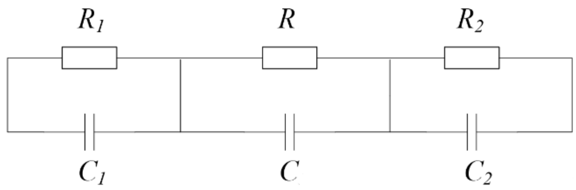


FIGURE 2. Equivalent circuit of the voltage division structure.

gap is approximately ($R_1 + R_2$): R. Under self-breakdown mode, R_1, R, and R_2 were all removed.

The equivalent circuit of the experiment platform is shown in Figure 3. The primary source was an 8-stage bipolar charging Marx generator whose equivalent capacitance C_m, inductance L_m, and resistance R_m were about 2.5nF, 4.75μH, and 8.3Ω, respectively. The Marx generated pulses with the full-wave rise time of about 100ns (period of the sine wave was about 400ns, equivalent frequency of the pulse was about 1/400ns = 2.5MHz) and amplitude from 150kV to 900kV. A 300pF transfer capacitor C_t was charged by the primary stage. The equivalent inductance of transfer stage L_t was about 2.5μH, and the load resistor R_L was 60Ω. A 1.1Ω resistor was installed at CH1 to measure the charging current of C_t. The voltage on the switch before breakdown was integrated from the current through C_t. A Rogowski Coil was installed at CH2 to measure the current through the transfer switch after breakdown.

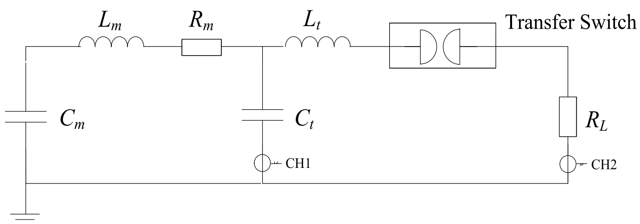


FIGURE 3. Equivalent circuit of the experimental platform.

The breakdown time delay (t_d) of the switch was defined as the time difference between the 10%-peak point of the voltage waveform and the 10%-peak point of the current waveform, which is demonstrated in Figure 4. The breakdown voltage was defined as the peak voltage on C_t considering that the switch broke down at the front edge of input pulses.

B. EXPERIMENTAL METHODS AND DATA PROCESSING

Breakdown characteristics of the transfer switch under self-breakdown mode and pre-ionization mode were tested when its working medium was nitrogen and operating gas pressure changed from 0.1MPa to 0.7MPa. The charging polarity was also a variable in the experiments. Before formal experiments, main electrodes, trigger electrodes, metal plane, and shell of the switch were cleaned by absolute alcohol.

To obtain higher energy transfer efficiency, the charging voltage of the Marx generator was adjusted to make the transfer switch break down at about 95% of the peak time

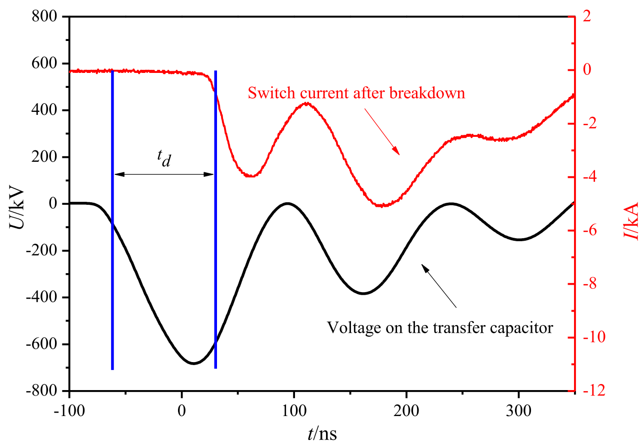


FIGURE 4. Reading method of the breakdown time delay.

of the input pulses. To analyze the breakdown jitter of the transfer switch, 20-50 shots data were obtained under each condition. The jitter of t_d was used to represent the switch jitter, and it was defined as the sample standard deviation of t_d. Between two shots there was a time interval of more than 1min.

III. EXPERIMENTAL RESULTS

A. SELF-BREAKDOWN AND VOLTAGE-SECOND CHARACTERISTICS

Because voltage waveform (without the breakdown of transfer switch) on C_t was a damped sine waveform, the transfer switch was scarcely possible to break down stably near the peak time under self-breakdown mode due to a small number of initial electrons and large statistical time delay jitter. Figure 5(a) demonstrates the breakdown types and proportions of the transfer switch under the self-breakdown mode, it indicates that the transfer switch might break down at the front edge (before the peak time), back edge (after the peak time) or fail to break down during the whole pulse, and this phenomenon almost always existed as the gas pressure and polarity of input pulses varied. Back edge breakdown and no breakdown cases will harm the insulation of transfer capacitor and following stages, and will also make the waveform on the load unacceptable, so these cases are unallowable in practice.

Table 1 shows statistical data of front edge breakdown cases. The max-min difference value of breakdown time delay was between 20ns and 50ns, the time delay jitter was approximately from 5.5ns to 15.5ns. So a self-breakdown switch cannot be applied in the cascade or parallel system also because that such volatility of time delay might bring about larger jitter of the whole pulsed power system.

Figure 6 shows a typical breakdown time delay distribution of the transfer switch (0.5MPa, under positive pulses) as input pulse's rising rate du/dt varied in a small range, in which the breakdown time delay of the no-breakdown case is defined as zero. It is implied that the breakdown time delay decreased slowly (namely the switch tended to break down at the front edge) as du/dt increased. This phe-

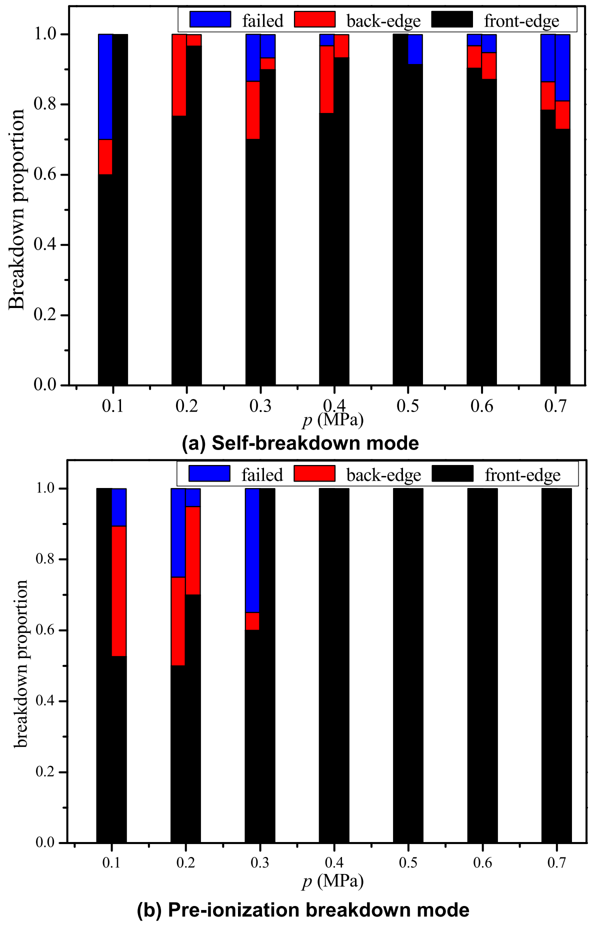


FIGURE 5. Breakdown types and proportions under self-breakdown mode and pre-ionization breakdown mode. (Under the same pressure, the left bar is the result of positive charging cases, the right bar is the result of negative charging cases).

TABLE 1. Statistical data of front edge breakdown cases under self-breakdown mode.

Charging polarity	Gas pressure/ MPa	Mean t_d/ns	Range of t_d/ns	Jitter of t_d/ns
Negative	0.1	76.7	[70.4, 88.0]	5.5
	0.2	94.2	[77.2, 105.2]	6.5
	0.3	93.4	[74.0, 106.4]	9.0
	0.4	83.2	[66.0, 104.0]	9.5
	0.5	83.1	[63.6, 99.6]	8.6
	0.6	91.7	[70.8, 109.6]	9.6
	0.7	89.2	[70.0, 106.0]	9.9
Positive	0.1	85.6	[61.2, 109.2]	15.5
	0.2	85.0	[66.0, 107.6]	12.1
	0.3	84.4	[71.6, 106.0]	9.4
	0.4	84.4	[72.0, 99.2]	7.7
	0.5	81.6	[67.2, 98.0]	7.6
	0.6	93.6	[82.0, 108.0]	6.9
	0.7	85.1	[70.8, 104.4]	8.5

nomenon partly agrees well with the voltage-second characteristic in high voltage engineering [6], but back edge breakdown and no-breakdown cases occurred when *du/dt* was decreased to make the switch break down near the peak time.

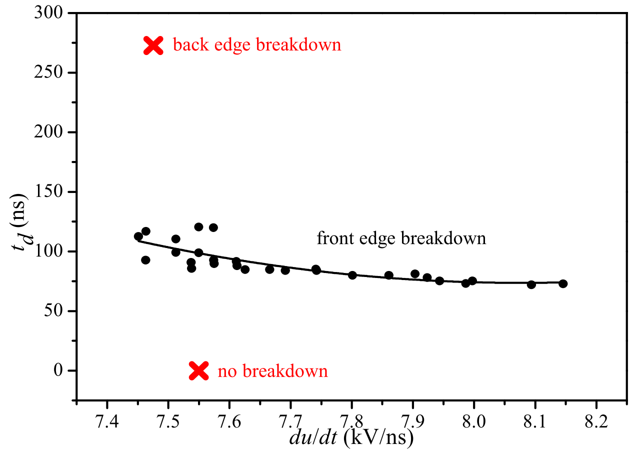


FIGURE 6. Breakdown time delay under different *du/dt*.

Because the peak electric field strength in the switch under different gas pressure was from 50kV/cm to 200kV/cm, only field emission current was insufficient to produce enough initial electrons, natural background radiation and field emission considering dielectric impurities on cathode surface might be main sources of initial electrons and statistical time delay jitter was a dominant part [18], [19]. Once the switch failed to break down before the peak time due to a long statistical time delay, then the voltage on the gap began to fall quickly and the electron avalanche process might be interrupted. Thus, no-breakdown or back edge breakdown could happen. This indicates why it is almost impossible to satisfy the stability requirement and high energy transfer efficiency simultaneously under self-breakdown mode for the transfer switch. So a pre-ionization source for the switch is indispensable.

B. PRE-IONIZED BREAKDOWN CHARACTERISTICS

It is important to note how the pre-ionization works [5], [15]. From Figure 1(c) we can see that the main gap electric field is designed to be shielded at the trigger gap, and it is impossible that the electrons in the arc channel of the trigger gap lead to an electron avalanche and breakdown of the main gap. Considering that the first ionization energy of nitrogen molecule is about 15.5eV, and the photon's energy is in the range of 3.1eV to 3.9eV [15], so it is also impossible that photons generated by spark discharge will ionize the nitrogen molecules and initiate an electron avalanche near the trigger gap. The work function of stainless steel is about 4.4eV, but the photons are generated when the electric field strength at the cathode surface is high enough, the actual work function will be smaller than 4.4eV. So the working mechanism of pre-ionization is more likely that the UV photons generated by spark discharge impact the cathode and generate initial electrons by photoemission, then the initial electrons generate secondary electrons by collision ionization.

To generate initial electrons as early as possible and reduce the breakdown jitter of the trigger gap, the share of the voltage on the trigger gap (the rising rate *du/dt* at the same time) should be the highest among possible values. So under the pre-ionization mode, R_1 and R_2 in Figure 2 were both chosen as 28kΩ considering the power requirement of paralleled resistors, and R was removed, so the voltage division ratio was about 14:1 (($R_1 + R_2$): ($1/2\pi fC$)).

Figure 5(b) and Table 2 indicates that the transfer switch could break down stably near the peak time under the pre-ionization mode, the max-min difference value of breakdown time delay was no more than 16.2ns, and time delay jitter was from 2ns to 4ns as gas pressure varied from 0.4MPa to 0.7MPa. However, under both charging polarities when the gas pressure was from 0.1MPa to 0.3MPa, back edge breakdown and no-breakdown cases occurred again (as Figure 5(b) indicates), the breakdown time delay jitter of front edge breakdown cases was from 5ns to 13.2ns (as Table 2 indicates), and the breakdown voltage under the self-breakdown mode and the pre-ionization mode was almost the same (as Figure 8 indicates), which means that the pre-ionization was nearly ineffective.

TABLE 2. Statistic data of front edge breakdown cases under pre-ionization mode.

Charging polarity	Gas pressure /MPa	Mean t_d/ns	Range of t_d/ns	Jitter of t_d/ns
Negative	0.1	83.6	[63.4, 98.2]	13.2
	0.2	81.1	[71.0, 94.4]	7.7
	0.3	99.9	[82.4, 114.0]	9.0
	0.4	99.3	[92.8, 106.8]	3.3
	0.5	96.9	[91.4, 103.2]	2.5
	0.6	96.2	[88.8, 101.8]	3.2
	0.7	97.5	[93.2, 104.0]	3.4
Positive	0.1	72.1	[51.4, 84.2]	10.3
	0.2	80.6	[67.4, 102.2]	10.7
	0.3	101.1	[90.2, 108.4]	5.2
	0.4	100.0	[94.6, 107.2]	3.7
	0.5	96.1	[90.2, 106.4]	3.8
	0.6	96.3	[94.6, 100.8]	1.6
	0.7	98.9	[95.6, 106.8]	2.9

Based on the mean breakdown voltage of the transfer switch, mean rising time of the input pulses and voltage division ratio, *du/dt* of the trigger gap can be figured out. The breakdown voltage of the trigger gap $U_{trigger}$ is calculated by the empirical formula, it can be inferred that the breakdown time delay of the trigger gap increased as gas pressure increased. The calculation result of negative charging cases is shown in Figure 7. It can be observed that the breakdown time delay of the trigger gap was between 27ns and 35ns when gas pressure ranged from 0.1MPa to 0.3MPa, but it was more than 40ns when the gas pressure ranged from 0.4MPa to 0.7MPa.

Effective UV illumination started to appear when the trigger gap broke down. Initial electrons in the main gap generated by cathode photoemission mainly appeared when UV illumination appeared, and UV illumination only sustained for a short period, not during the whole spark discharge process [15], so the initial electrons could only appear during a specific time. It should be specially noted that the electrons

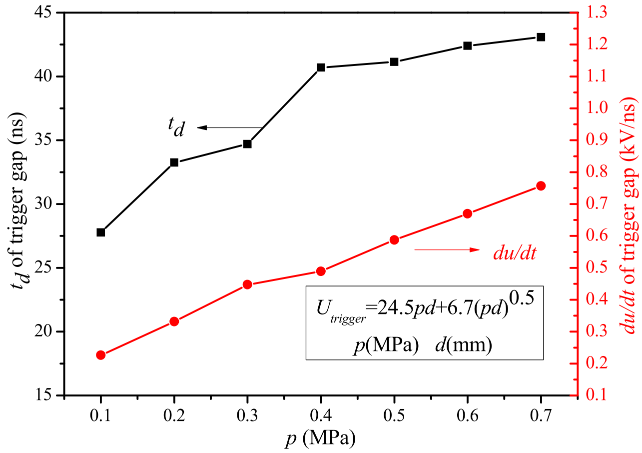


FIGURE 7. Breakdown time delay and *du/dt* of the trigger gap.

in the arc channel of the trigger gap could not drift towards the main gap anode (and become initial electrons) because the trigger plane shielded the main gap electric field at the trigger gap.

The reason for an invalid pre-ionization under low gas pressure might be the early breakdown of the trigger gap. The normalized electric field E/p was not high enough in the main gap when the trigger gap breaks down, which made it hard for initial electrons to initiate an effective electron avalanche immediately after their generation. This assumption will be further analyzed in the next section.

C. POLARITY EFFECT

To obtain a high voltage pulse by superposition of two bipolar pulses generated by two pulse generators with the same structure but different charging polarities, the polarity effect of breakdown voltages of transfer switches should also be considered.

Figure 8 exhibits the breakdown voltage of the transfer switch under different charging polarities. The mean breakdown voltage under pre-ionization mode was generally lower than that under self-breakdown mode when gas pressure was

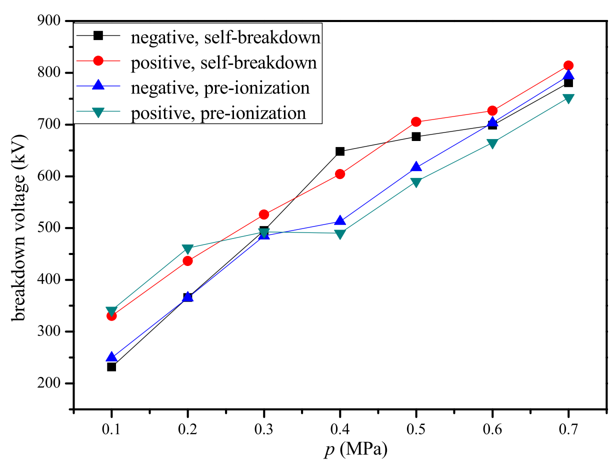


FIGURE 8. Breakdown voltage under different charging polarities.

the same because there was a steady source of initial electrons under pre-ionization mode.

The mean breakdown voltage made a difference as the mean breakdown time delay was close under positive and negative pulses. Changing the polarity of input pulses was actually exchanging the cathodes and anodes of the main gap and the trigger gap. Because there were back edge breakdown and no-breakdown cases, it is difficult to compare the polarity effect in breakdown voltage under self-breakdown mode. Generally, the self-breakdown voltage was a little higher under positive pulses. While the micro surface topography on the cathode influences the field emission current (one possible source of initial electrons), when the previous cathode and anode exchange their role because the polarity of input pulse changes and the electrical connection of the experimental circuit did not change, a slight difference of electrode surface might bring about the difference in the average breakdown voltage. And the output characteristic of the Marx generator was different under different charging polarity, which might also lead to the difference in breakdown voltage. Besides, the trigger gap electrodes were not symmetrical and the two trigger electrodes were made of different materials, the generating time of initial electrons under different polarities might also vary under the pre-ionization mode, so mean breakdown voltage under negative pulses was generally higher under the pre-ionization mode.

On the whole, the polarity effect of breakdown voltage was not obvious under both modes due to the symmetry of main gap electrodes, and breakdown characteristics can be obtained by experiments under negative or positive charging cases.

IV. INFLUENCE MECHANISM OF PRE-IONIZATION

To explain why pre-ionization under low gas pressure was ineffective, the ability of initial electrons with different generating times and numbers to initiate an electron avalanche should be analyzed. The probability model [18] and diagnosis results [15] are used for reference in this section to analyze the influence of generating time and rate of initial electrons on the pre-ionization effect.

A. PROBABILITY DISTRIBUTION MODEL OF EFFECTIVE ELECTRON AVALANCHE'S INITIATION UNDER PULSED ELECTRICAL FIELD

Because the formative time delay accounts for a relatively small part in the breakdown time delay of a pulsed switch whose gap distance is several centimeters and operating electric field is several hundred kV/cm, the generation process of initial electrons and effective electron avalanche's initiation mainly decide the switch's breakdown time delay jitter.

The probability distribution model [18] of effective electron avalanche's initiation under pulsed electric field depends on both generating rate of initial electrons and normalized electric field E/p in the gap, which has a more complex form than that under DC electric field because the electric field under pulse voltage is time-varying [13].

Because the enhanced field factor of the main gap in the transfer switch was <2, which corresponded to a slightly non-uniform field, and initial electrons were mainly generated at the cathode by optical illumination, the surface condition of main electrodes had little impact on the generation of initial electrons, to get a qualitative consequence, the model [18] is simplified as below.

The probability of starting an effective electron avalanche under specific electric field E, gas pressure p, time t during time interval dt has the following form

$$dF(E(t), p, t) = dG(t) \cdot S(E(t), p) \tag{1}$$

in (1) dF is the probability of an effective electron avalanche's initiation, dG is the probability of the appearance of initial electrons, S is the breakdown probability once an initial electron appears.

dG in time interval dt has the following form

$$dG(t) = (\dot{n}_0(t) + \dot{n}_e(t)) \cdot dt \tag{2}$$

in (2) $\dot{n}_0$ is the generating rate of electrons by natural radiation, $\dot{n}_e$ is the generating rate of initial electrons by other mechanisms like field emission and optical illumination.

The influence of attachment is ignored because the working medium in the transfer switch is nitrogen.

S is related to the electric field E and gas pressure p because they determine the ionization coefficient $\alpha(E/p)$. To start an effective electron avalanche, the ionization coefficient α should satisfy

$$\int_0^{d_C} \alpha(x)dx \geq K_C \tag{3}$$

in (3) d_C is the critical length of electron avalanche, K_C is the criterion of transition from an electron avalanche to a streamer.

Considering the gap structure and field enhancement, breakdown probability $S(E(t),p)$ should have the following form

$$S(E(t), p) = k \cdot S'(E_{av}(t), p) \tag{4}$$

in (4) k represents the influence of gap structure, and S' is only determined by E_{av} and p.

When the pulsed electric field is much smaller than the DC breakdown electric field, the breakdown probability S is near zero. Without an extra source of initial electrons, DC breakdown strength can be seen as the lowest strength that the gap can break down with a single initial electron in the gap, so we assume that the breakdown probability is equal to 1 when the pulsed electric field strength is equal to or greater than the DC breakdown field strength. If the input pulse voltage is a sine wave with an equivalent frequency of 2.5MHz, S will have the characteristics in Figure 9 (assuming that the maximum electric field is equal to the DC breakdown electric field).

When gas pressure p, waveform of input pulse voltage and gap structure are fixed, the probability of starting an effective

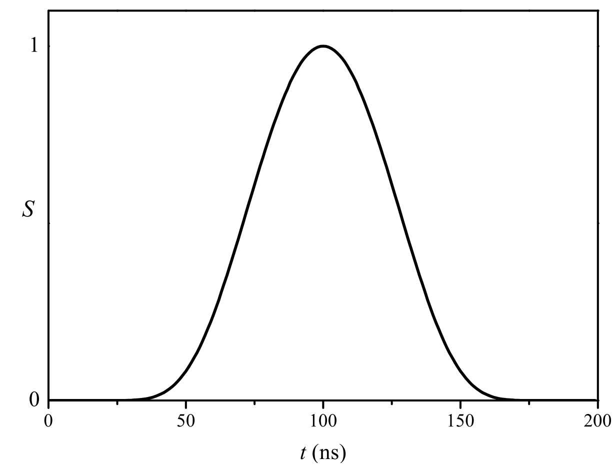


FIGURE 9. Shape of S.

electron avalanche is only related to the generating rate of initial electrons and time t. So dF is in the following form

$$dF(t) = (\dot{n}_0 (t) + \dot{n}_e (t)) \cdot S (t) dt \quad (5)$$

Based on conditional probability theory, if the time interval dt is small enough and the electron avalanche didn't start before t, the conditional probability that the electron avalanche starts during t and $t + dt$ is $(dF(t)/dt)dt$, so we have

$$F (t + dt) - F (t) = dF (t) = \frac{dF (t)}{dt} \cdot dt \cdot (1 - F (t)) \quad (6)$$

$$\frac{d (1 - F (t))}{(1 - F (t))} = -\frac{dF (t)}{dt} \cdot dt \quad (7)$$

$$\ln (1 - F (t)) = \int_{t_0}^{t} -\frac{dF (t)}{dt} \cdot dt \quad (8)$$

$$F (t) = 1 - \exp\left(\int_{t_0}^{t} -\frac{dF (t)}{dt} \cdot dt\right) = 1 - \exp\left(\int_{t_0}^{t} - (\dot{n}_0 (t) + \dot{n}_e (t)) S (t) dt\right) \quad (9)$$

As the shape of S is already known, the characteristics of $F(t)$ can be inferred by the generating rate of initial electrons.

B. INFLUENCE OF GENERATING TIME AND RATE OF INITIAL ELECTRONS

When the initial electrons are generated by a pre-ionization source (spark discharge of the trigger gap), the influence of natural radiation is relatively small, and the field strength is not enough to generate initial electrons by field emission, so we only consider the $\dot{n}_e$ item which is due to the pre-ionization. The time jitter of the mm trigger gap is in the range of 0.5ns to 1.5ns based on previous experimental results. However, it is difficult to measure the exact time jitter of the trigger gap when the switch is operated due to the switch structure. The empirical results indicate that the time jitter is smaller when the *du/dt* on the gap is larger. It leads to a confusing phenomenon because the switch jitter was very large when the time jitter of the trigger gap was small (because the trigger gap got a large share of the switch voltage and broke down early, namely the *du/dt* on the trigger gap was large under the previous pre-ionization mode). Obviously, the time jitter of the trigger gap (the pre-ionization source) wasn't, while the introducing time was the main influence factor of the switch jitter. To simplify the analysis, the time jitter of the pre-ionization source is ignored.

Diagnosis results indicate that the rise time of UV optical pulse was smaller than 5ns when the trigger gap had a slightly non-uniform field, and FWHM of UV optical pulse was smaller than 15ns when there was no energy storage capacitor (Cs) in parallel with the gap [15]. The typical waveform of the UV optical pulse (central wavelength 337 nm) is shown in Figure 10 [15].

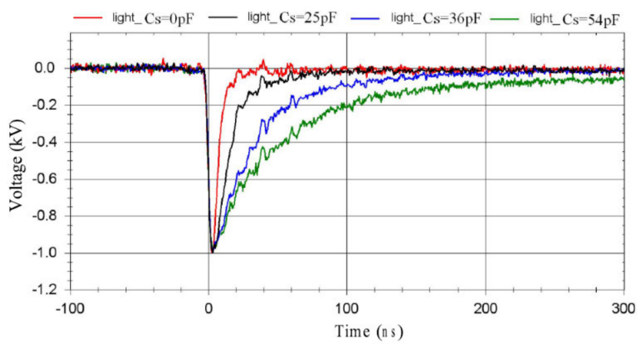


FIGURE 10. A typical waveform of the UV optical pulse [15].

Because the generating rate of electrons is proportional to the intensity of UV pre-ionization illumination [20], the waveform of UV optical pulse when the trigger gap breaks down can be used to qualitatively represent the shape of $\dot{n}_e$. Only UV light should be taken into account because only UV photons seem to have enough energy to lead to photoemission at the main gap cathode [15].

Figure 11 demonstrates a combination of S and $\dot{n}_e$, the input pulse voltage is a damped sine wave with an equivalent frequency of 2.5MHz (starts at $t = 0$) and the optical pulse starts at $t = 30$ns, so it can be used to analyze the breakdown characteristics of the transfer switch under the pre-ionization mode.

In Figure 11, O is the overlap of S and $\dot{n}_e$, which substantially determines the characteristics of F. Before $t = 30$ns, there are no initial electrons in the main gap, so the area of O is zero and the value of F is zero. As the timeline shifts from $t = 30$ns in the positive direction, the area of O and the value of F increases. When the area of O is large enough to make the value of F equal to one, it is ensured that the breakdown process will happen during the pulse. However, if the area of O is not large enough to make the value of F equal to one at

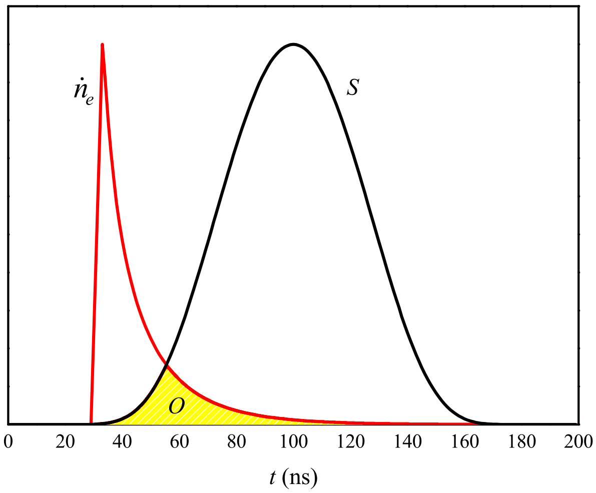


FIGURE 11. Combination of S and $\dot{n}_e$.

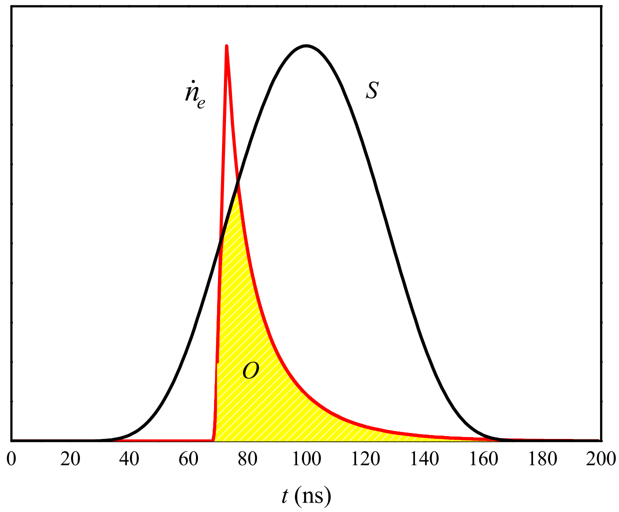


FIGURE 12. Combination of S and $\dot{n}_e$ when the pre-ionization is postponed.

the peak time of input pulse voltage (t = 100ns), back edge breakdown or no breakdown cases might happen.

Thus, the experimental phenomenon can be explained by the above inference. While the gas pressure is low, the trigger gap breaks down earlier, the area of O is smaller. Probably, the area of O at the peak time of input pulse is not large enough to make the value of F equal to one, which brings about back edge breakdown and no breakdown cases. While the gas pressure is higher, the trigger gap breaks down later, the area of O may be large enough to make the value of F equal to one at the peak time of input pulse, so back edge breakdown and no breakdown cases can be averted.

To avoid back edge breakdown and no breakdown cases and reduce the breakdown time delay jitter, the area of O at the peak time of input pulse and the increasing rate of the area of O as timeline shifts should be large enough to make sure that the value of F increases rapidly from zero to one, namely the breakdown time delay has a steep distribution curve. Obviously, the combination in Figure 11 can't meet the above requirements.

To meet the above requirements, the combination of S and $\dot{n}_e$ should have the characteristics in Figure 12 or Figure 13.

In Figure 12, the curve of $\dot{n}_e$ is shifted behind. It is observed that the area of O increases faster and it can reach a large value at the peak time of input pulse. It means the value of F can increase from zero to one quickly, and the switch has a low breakdown jitter due to good coordination of S and $\dot{n}_e$.

In Figure 13, the curve of $\dot{n}_e$ has a wider FWHM. Although the curve of $\dot{n}_e$ is not shifted behind, the area of O can still increase quickly because the value of $\dot{n}_e$ is maintained at a high level for a longer time. So a low breakdown jitter can also be realized.

Based on Figure 12 and Figure 13, two methods can be utilized to improve the effectiveness of pre-ionization in the switch:

1) Enlarge the voltage division ratio and postpone the breakdown of the trigger gap, so the curve of $\dot{n}_e$ is shifted behind.

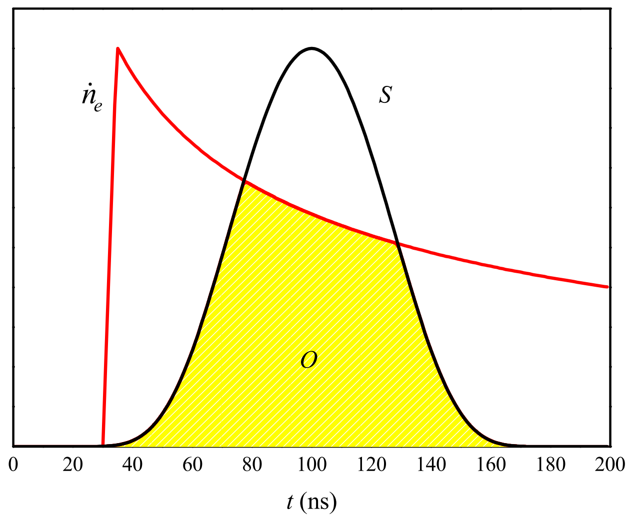


FIGURE 13. Combination of S and $\dot{n}_e$ when the FWHM of $\dot{n}_e$ is wider.

2) Enlarge the hole of the trigger plane, so the trigger plane cannot shield the main gap electric field at the trigger gap. Because the main gap electric field is perpendicular to the trigger gap electric field, the electrons in the arc channel of the trigger gap can drift towards the main gap anode and become initial electrons in the main gap even the trigger gap breaks down at the beginning, the curve of $\dot{n}_e$ will have a wider FWHM.

V. IMPROVEMENT APPROACHES AND RESULTS

This paper is an extension of the previous results [21]. The experimental phenomena were explained by the above model, and the following improvements were carried out under the guidance of the above analysis, a much better performance was obtained.

A. APPROACH 1: CHANGING THE VOLTAGE DIVISION RATIO

To postpone the pre-ionization, a 2kΩ resistor was paralleled with the trigger gap, so the voltage division ratio between the main gap and the trigger gap was approximately 28:1. Because the polarity effect was not obvious, so experiments in this section were only conducted under negative pulses.

Table 3 demonstrates the experimental results of the transfer switch under the above voltage division ratio. It was observed that back edge breakdown and no breakdown cases didn't occur when gas pressure varied from 0.1MPa to 0.7MPa. And the breakdown jitter characteristics were improved significantly. The breakdown time delay jitter was no more than 2.5ns under each gas pressure and no more than 1.6ns when gas pressure was from 0.3MPa to 0.7MPa. The max-min difference value of breakdown time delay was no more than 12ns under each gas pressure and no more than 8ns when gas pressure was from 0.3MPa to 0.7MPa.

TABLE 3. Data of breakdown cases as pre-ionization was postponed.

Gas pressure/ MPa	Mean breakdown voltage/kV	Mean t_d/ns	Range of t_d/ns	Jitter of t_d/ns
0.1	193.2	99.4	[94.2, 106.2]	2.5
0.2	311.3	99.5	[95.8, 105.4]	2.0
0.3	423.9	99.1	[97.0, 101.0]	0.9
0.4	519.2	101.2	[98.6, 103.8]	1.2
0.5	630.8	100.2	[96.6, 102.2]	1.0
0.6	717.9	100.2	[97.0, 104.2]	1.6
0.7	804.7	99.1	[95.0, 103.0]	1.6

B. APPROACH 2: ENLARGING THE HOLE OF TRIGGER PLANE

To make the electrons in the arc channel of the trigger gap become initial electrons in the main gap and broaden the FWHM of $\dot{n}_e$, the diameter of the hole at the trigger plane was enlarged from 1.5cm to 11.2cm, the main gap distance was still 7cm, and the trigger gap distance was reduced to 1mm. Figure 14 shows the appearance of the modified switch. A 4kΩ resistor was paralleled with the trigger gap to make the voltage division ratio between the main gap and the trigger gap be approximately 14:1.

Due to the restriction of the Marx generator's capacity, the experiment of the modified switch was only carried out when gas pressure varied from 0.1MPa to 0.4MPa. Table 4 indicates that the stability of the switch could be obtained by a sustaining pre-ionization. The breakdown time delay jitter was no more than 1.5ns as gas pressure varied from 0.1MPa to 0.4MPa. The breakdown voltage of the modified switch was higher than the original switch under the same gas pressure due to an actually longer gap distance, it can be beneficial to the operation of pulse generator because the same breakdown voltage and low jitter characteristic can be obtained under lower gas pressure, which reduces the mechanical pressure of the insulation shell of the switch.

FIGURE 14. The appearance of the modified switch.

TABLE 4. Data of breakdown cases of the switch with a larger hole at the trigger plane.

Gas pressure/ MPa	Mean breakdown voltage/kV	Mean t_d/ns	Range of t_d/ns	Jitter of t_d/ns
0.1	339.0	70.9	[67.0, 73.8]	1.5
0.2	512.7	77.9	[75.4, 79.8]	1.1
0.3	665.6	82.8	[81.0, 85.8]	1.1
0.4	793.1	88.2	[85.4, 91.0]	1.5

VI. DISCUSSION

To compare the breakdown characteristics of the transfer switch under three pre-ionization modes and facilitate our analysis, the experimental data are compared under the same scale. Figure 15 demonstrates the breakdown time delay and jitter and Figure 16 demonstrates the peak value of the average normalized electric field (E_{av}/p) of the main gap.

To be convenient, we denote the switch under the original pre-ionization method, the switch adopting improvement approach 1, and the switch adopting improvement method 2 as switch 0, switch 1, and switch 2, respectively.

It is observed that the average breakdown time delay of switch 1 was a little longer than that of switch 0, and the breakdown time delay of switch 0 had a wider range, which was also reflected in the value of jitter. Because the peak values of the average normalized electric field (denoted as E_{av}/p) in switch 0 and switch 1 were roughly the same, which means the changing process of E_{av}/p and the shape of S were also roughly the same, this phenomenon was mainly due to the characteristic of pre-ionization (shape of $\dot{n}_e$). This phenomenon can be explained in Figure 11 and Figure 12, which correspond to the working modes of switch 0 and switch 1, respectively. Because $\dot{n}_e$ is shifted behind in Figure 12, the area of O starts to increase later but increases faster, the average breakdown time delay of switch 1 was a little longer than that of switch 0, and switch 1 had a smaller jitter. And here was an interesting thing, 0.1MPa led to the highest peak E_{av}/p in switch 0, but switch 0 couldn't break down stably under 0.1MPa. It means that the switch stability can only be obtained by the coordination of $\dot{n}_e$ and S under the structure of switch 0 and

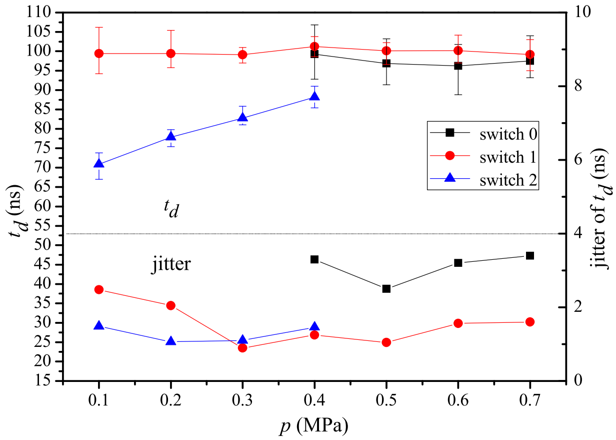


FIGURE 15. Breakdown time delay and jitter of three switches.

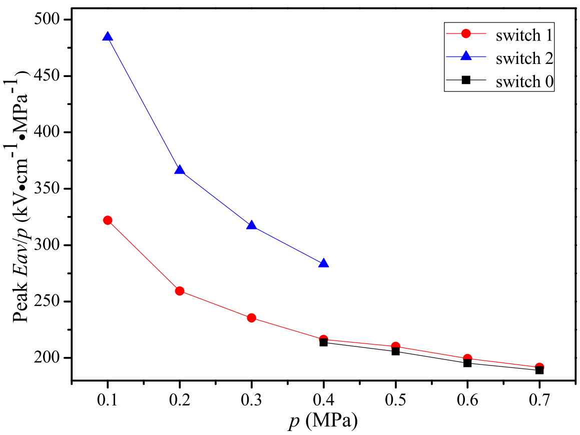


FIGURE 16. Peak E_{av}/p value of three switches.

switch 1. The breakdown voltage of the trigger gap under higher gas pressure tended to be higher. However, due to the radiative characteristics of nitrogen correlated to the gas pressure [22], the intensity of UV optical pulse might not increase as the gas pressure increased and the absolute value of $\dot{n}_e$ under higher gas pressure might not be larger. Meanwhile, the average E/p in the switch gap became smaller as the gas pressure increased. These partly explain why the switch jitter of switch 0 and switch 1 increased as the gas pressure increased from 0.5MPa to 0.7MPa.

The average breakdown time delay of switch 2 was the shortest among the three switches. Intuitively, as Figure 13 shows, though trigger gap broke down early in switch 2, the electrons in the arc channel of trigger gap could become initial electrons and drift towards the main gap anode, so the FWHM of $\dot{n}_e$ was wide enough to make sure that pre-ionization was effective. Actually, the physic process might be more complicated. First, the electron avalanche in switch 2 could initiate at the main gap cathode, or the trigger gap, even at both places. Second, the initial electrons in the main gap might be generated earlier than the breakdown of the trigger gap because the electrons in the electron avalanche process of the trigger gap might drift towards the main gap anode through the effect of the main gap electric field. So the low jitter characteristic of switch 2 might be attributed to multiple causes, and Figure 13 could largely illustrate the working mechanism. Because the number of initial electrons in switch 2 was much bigger than that in switch 0 or switch 1, the coordination of S and $\dot{n}_e$ might not be as important as that in switch 0 and switch 1.

Besides, the breakdown jitter of the trigger gap was not considered in the probability distribution model, actually, it will result in the jitter of $\dot{n}_e$, so it also needs to be taken into consideration to get a more precise and quantitative model.

The diagram of cumulative breakdown probability can be deduced (given in Figure 17). Switch 1 and switch 2 both had low breakdown time delay jitters, so their cumulative distribution functions (CDF) are revealed as fast-rising curves and their time delays have a small range. Switch 2 had a shorter average time delay, so its CDF curve starts rising earlier. Switch 0 had the biggest jitter and widest range of breakdown time delay, so its CDF curve rises more slowly. Actually, the CDF curves in Figure 17 can also be derived from Figure 11 to Figure 13.

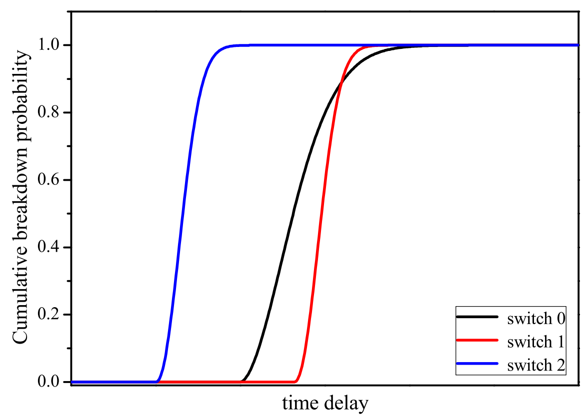


FIGURE 17. Diagram of the cumulative breakdown probability of three switches.

For practice use, switch 2 seems to be a better choice because the voltage division ratio needn't be chosen in a small range, and high breakdown voltage and low jitter characteristics can be realized under lower gas pressure than switch 1.

VII. CONCLUSION

According to the above discussions, we can come to the following conclusions.

1) UV-illumination in a self-triggered pre-ionization switch can be generated by the breakdown of a trigger gap as the voltage on it is divided from the main gap by parallel resistors, it can work as a pre-ionization source and the breakdown time delay jitter could be reduced. But the pre-ionization might be ineffective due to the premature breakdown of the trigger gap. The polarity effect of breakdown voltage was not obvious due to the approximate symmetry of the main gap electrodes.

2) Breakdown characteristics of the pulsed transfer switch can be explained by the probability distribution model of

effective electron avalanche's initiation. The probability distribution model is determined by the generating rate of initial electrons $\dot{n}_e$ and the breakdown probability S. To reduce the switch jitter, $\dot{n}_e$ and S should have good coordination to make sure the initial electrons are effective.

3) There are two approaches to reduce the breakdown time delay jitter of the pre-ionization transfer switch. The first approach is to optimize the coordination of $\dot{n}_e$ and S by making the trigger gap break down as the normalized electric field in the main gap is already high enough to initiate an electron avalanche. The second approach is to increase the absolute value and FWHM of $\dot{n}_e$ by enlarging the hole of the trigger electrodes plane (eliminating the shielding of the main gap electric field at the trigger gap) and letting the electrons in the arc channel of the trigger gap become initial electrons in the main gap. When the switch broke down at about 95% of the peak time, its breakdown time delay jitter could be reduced to 1ns-2ns by adopting the above two methods.

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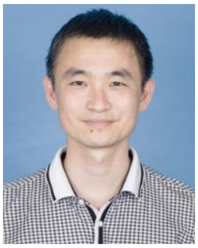
TIANCHI WANG was born in Jiangsu, China, in 1996. He received the B.S. degree in electrical engineering from Xi'an Jiaotong University, in 2018. He is currently pursuing the Ph.D. degree with the Department of Engineering Physics, Tsinghua University. His current research interest includes pulsed gas switches.



HAIYANG WANG was born in Shanxi, China, in 1979. He received the Ph.D. degree in nuclear science and technology from the Northwest Institute of Nuclear Technology, in 2015. His current research interests include pulsed power technology and generation of electromagnetic pulse.

WEI CHEN was born in Shaanxi, China, in 1968. He received the Ph.D. degree in nuclear science and technology from Xi'an Jiaotong University, in 1998. His current research interests include radiation effects and generation of radiation environment.

TAO HUANG was born in Heilongjiang, China, in 1980. He received the Ph.D. degree in nuclear science and technology from the Northwest Institute of Nuclear Technology, in 2020. His current research interests include high power gas switches and pulsed power technology.