Optical Diagnostics of Multi-Gap Gas Switches for Linear Transformer Drivers

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Abstract The trigger characteristics of a multi-gap gas switch with double insulating layers, a square-groove electrode supporter and a UV pre-ionizing structure are investigated aided by a high sensitivity fiber-bundle array detector, a UV fiber detector, and a framing camera, in addition to standard electrical diagnostics. The fiber-bundle-array detector is used to track the turn-on sequence of each electrode gap at a timing precision of 0.6 ns. Each fiber bundle, including five fibers with different azimuth angles, aims at the whole emitting area of each electrode gap and is fed to a photomultiplier tube. The UV fiber detector with a spectrum response of 260-320 nm, including a fused-quartz fiber of 200 µm in diameter and a solar-blinded photomultiplier tube, is adopted to study the effect of UV pre-ionizing on trigger characteristics. The framing camera, with a capacity of 4 frames per shot and an exposure time of 5 ns, is employed to capture the evolution of channel arcs. Based on the turn-on light signal of each electrode gap, the breakdown delay is divided into statistical delay and formative delay. A decrease in both of them, a smaller switch jitter and more channel arcs are observed with lower gas pressure. An increase in trigger voltage can reduce the statistical delay and its jitter, while higher trigger voltage has a relatively small influence on the formative delay and the number of channel arcs. With the UV pre-ionizing structure at 0.24 MPa gas pressure and 60 kV trigger voltage, the statistical delay and its jitter can be reduced by 1.8 ns and 0.67 ns, while the formative delay and its jitter can only be reduced by 0.5 ns and 0.25 ns.

Keywords: optical diagnostics, multi-gap gas switches, linear transformer driver

PACS: 51.50.+v, 52.70.Kz, 84.70.+p

DOI: 10.1088/1009-0630/16/7/08

(Some figures may appear in colour only in the online journal)

1 Introduction

The linear transformer driver (LTD) is a newly developed pulsed-power facility [1]. It can considerably reduce the size and cost of high-current pulsed-power accelerators. For the applications of inertial confinement fusion (ICF), isentropic compression experiments (ICE), and radiography sources, an accelerator may include a total of 50000 gas switches [2]. Therefore, the performance of an LTD strongly depends on the parameters of gas switches. As one alternative design of gas switches, multi-gap gas switches are extensively used in LTD prototypes thanks to their relatively low working gas pressure, low trigger voltage, and capacity of forming multi-channel arcs [3].

Inspired by the baseline design of gas switches at the High Current Electronics Institute (HCEI) in Russia [4,5], we investigated several different structures of multi-gap gas switches [6,7]. A 12-brick LTD module with a peak current of 115 kA and a rise time of 89 ns was also developed to test the overall switch performance [8]. Typical parameters, such as lifetime, inductance, and failure rate, were used to characterize the performance of the gas switches. However, such parameters do not have a sufficient capability of unmasking the complex physics that happens within gas switches and governs their performance. The physics involved in the gas breakdown in each electrode gap, the formation of channel arcs, and the evolution of streamers is still not well understood. Optical diagnostics has been proved to be essential and helpful for investigating these underlying physics of switches with various structures [3,8–12].

Recently, we have developed a multi-gap gas switch with a novel geometric structure. Double insulating layers were used to improve the switch lifetime and a
square-groove structure of inner insulator was utilized to enhance the mechanical reliability of the switch \[13\]. A pre-ionizing structure mounted at the center of the trigger electrode was used to test its impact on trigger jitter and trigger voltage \[14\]. In order to investigate the fundamental principles of this gas switch operation, we developed three optical diagnostics, i.e., a high-sensitivity fiber array detector, a solar-blinded fiber detector, and a high-speed framing camera. In this paper, we mainly concentrate on the discussion of the influence of operation conditions of gas switches on their trigger breakdown characteristics utilizing these optical diagnostic results.

2 Switch configuration and optical diagnostic systems

The configuration of the newly designed switch and the setup of fiber detectors are shown in Fig. 1. This switch, which is 145 mm in height and 150 mm in diameter, has six uniform 5 mm electrode gaps and is filled with 0.15-0.28 MPa dry air in our experiments. A double insulating layer made of polyethylene is used to maintain high resistance during discharges, and it is capable of extending the switch lifetime to more than 5500 shots without any prefire at 170 kV charge voltage and 28 kA peak current. A square groove is used to brace the electrodes, which can enhance the mechanical reliability and keep each gap at a uniform distance. Two thorium-tungsten alloy needles with adjustable distance are mounted on the center of the triggered electrode to produce UV light.

![Fig.1 Configuration of the gas switch and the setup of fiber detector](image1)

The high-sensitivity fiber-bundle detector array consists of six fiber bundles and six photomultiplier tubes (PMTs) and is used to acquire the accurate turn-on time of each electrode gap. Each fiber bundle consisting of five 62.5 µm multimode fibers with the same length is designed to aim at only one electrode gap based on the fiber numerical aperture of 0.2 and to enhance its detective efficiency. Each of the five fibers is positioned with different azimuth angle (see Fig. 2) so as to guarantee that all the light emitting from the channel arcs can be detected by the fiber bundle, as well as to make enough diagnostic access for the framing camera. The timing precision of this detector is less than 0.6 ns, considering that the maximum length difference in fibers leads to 0.3 ns, the maximum light length in electrode gap, 0.18 ns, and the PMT jitter, 0.1 ns.

![Fig.2 Azimuth distribution of the five fibers in a fiber bundle](image2)

A 200 µm fused-quartz fiber and a solar-blinded PMT constitute the UV fiber detector. A novel connector is designed to connect the fiber to the switch (see Fig. 3), which can totally seal the gas in switches for all the gas pressure tested in our experiments. The UV fiber inserted in the switch is 60 mm long. A ceramic ferrule is used to prevent the top part from destruction by discharges, and also used as the fiber supporter and insulator. The UV fiber detector is capable of responding the spectrum from 260 nm to 320 nm as compared to a standard UV Si detector.

![Fig.3 Configuration of the parts of the UV fiber detector connected to the switch](image3)

The framing camera utilizes a beam splitter prism to feed four objective images onto four separate micro-channel plate (MCP) image intensifiers, which are coupled with four charge coupled devices, respectively. The external trigger signal coming from the trigger system is fed into a synchronizing signal generator, and then the synchronizing signal triggers the gated-pulse generator to produce four gated signals with ~200 V voltage and 5 ns pulse duration to control the exposure time of MCP image intensifiers. The interval time between images is adjustable by altering the length of cables connecting the synchronizing generator to the gated-pulse generator.

3 Results and discussion

The electrode gaps are numbered 1#-6# from top to bottom of the switch. When tested, the switch is fixed in transformer oil and attached to two 40 nF capacitors.
The switch discharges to a 0.6-0.8 Ohm load and is triggered with a negative 50-80 kV trigger pulse. The top of the switch is positively charged. As expected, the turn-on sequence of the electrode gaps is 3#-2#-1#-4#-5#-6#, see Fig. 4 (50 kV trigger voltage, 150 kV charge voltage, 0.28 MPa gas pressure).

The trigger pulse arrives at the switch approximately 86 ns before the current starts. This time interval is defined as the trigger breakdown delay of the switch. The 3# gap is the triggered electrode gap which emits light about 33 ns after the trigger pulse. This time interval is defined as the statistical delay. The 2# and 1# gaps emit light about 5 ns and 11 ns after 3# gap, respectively. On the negatively charged side, 4# gap breakdown experiences about 32 ns delay after 1# gap. It takes 6 ns and 13 ns for 5# and 6# gap to break down after 4# gap, respectively. All the breakdown time of these six switch gaps is about 46 ns, which is defined as the formative delay. The ratio of statistical delay and formative delay approximately equals 1:1.15.

The images acquired by the framing camera of two shots are shown in Fig. 5 and the time of each image relative to the trigger pulse and the switch current is shown in Fig. 6. These images are blurred due to the refraction of the switch insulator, but they also indicate the same turn-on sequence of the gap electrodes. The channel arcs do not line up within the whole switch, while a straight discharge channel is observed on the positive charged side, so the effect of reducing switch inductances by forming multi-channel arcs still needs more investigation.

The influence of trigger voltage and gas pressure on the three defined delays and their jitters is shown in Fig. 7(a)-Fig. 9(b). Each data point presented here is an average of 30 shots. The switch shows a wide range of operating conditions with a jitter of less than 3.5 ns. When the switch works at 70 kV trigger voltage and 0.16 MPa gas pressure, its jitter is approximate 0.9 ns.
Both the statistical delay and the formative delay decrease with decreasing gas pressure, as well as their jitters. Lower gas pressure can statistically produce more channel arcs, see Table 1. From Fig. 8(a) and (b), the trigger voltage has a strong influence on the statistical delay. Compared with the gas pressure, the trigger voltage shows a relatively small impact on the formative delay when it is more than 60 kV apart from 0.24 MPa gas pressure, as shown in Fig. 9(a) and (b). Generally, smaller delay can result in smaller delay jitter, but the behavior of the switch is different under other operational conditions when the switch works at 0.24 MPa gas pressure. An explanation for this difference still needs to be found.

The number of channel arcs also weakly depends on the trigger voltage, see Table 2. As shown in Tables 1 and 2, the number of channel arcs in 2# gap and 5# gap is smaller than those in other gaps. Especially, 5# gap experiences higher breakdown voltage than the first four gaps, so it should have shown more channel arcs. There may be an opportunity to further improve the switch performance by altering the structures of 2# gap or 5# gap to enhance the formation of channel arcs.

A UV pre-ionizing structure has been used in other gas switches with different structures to improve the trigger performance [3]. A pair of UV pre-ionizing needles is added in the hole of the trigger electrode, see Fig. 10. The additional UV pre-ionizing structure does
not change the voltage distribution within the switch \[^{[14]}\]. The stability of UV light yield and the delay time relative to the trigger pulse depend on the distance between the two UV needles, see Fig. 11. When the distance is larger than 3.5 mm, the stability of UV light becomes very poor, and the jitter of the switch becomes larger compared with the case of no UV needles. The relation between the needle distance and the switch jitter is shown in Fig. 12 at 60 kV trigger voltage and 0.24 MPa gas pressure. When the distance varies from 1.5 mm to 3 mm, the switch jitter is reduced from 3 ns without UV pre-ionizing to less than 2 ns with UV pre-ionizing.

![Fig.10](image1)  Photo of the UV pre-ionizing structure

![Fig.11](image2)  UV light yield and its stability versus UV gap distance

![Fig.12](image3)  Switch jitter versus UV gap distances

The UV pre-ionizing structure can reduce switch jitter in a wide range of operating conditions. It can reduce the switch jitter by 36.2%, 25.3%, and 27.9% at 50 kV, 60 kV and 70 kV trigger voltage at 0.28 MPa gas pressure (see Fig. 13), respectively. When working at low gas pressure (such as 0.16 MPa), the UV pre-ionizing structure has no benefit to the reduction of the switch jitter at 60 kV trigger voltage. However, it can reduce the switch jitter by 27.4%, 14.7%, and 25.3% at 0.20 MPa, 0.24 MPa and 0.28 MPa gas pressure (see Fig. 14), respectively. Therefore, if the switch needs to operate at a certain gas pressure and jitter level, it can be easily triggered at relatively low voltage using the UV pre-ionizing structure.

![Fig.13](image4)  Influence of UV pre-ionizing structure on the switch jitter for different voltages (0.28 MPa gas pressure)
Influence of UV pre-ionizing structure on the switch jitter for different gas pressures (60 kV trigger voltage)

The UV pre-ionizing structure mainly affects the statistical delay and its jitter, while it has relatively small influence on formative delay and its jitter. With this structure at the same operating conditions (0.24 MPa gas pressure and 60 kV trigger voltage), the statistical delay and its jitter can respectively be further reduced by 1.8 ns and 0.67 ns, while the formative delay and its jitter can only be reduced by 0.5 ns and 0.25 ns, respectively.

4 Conclusion

A high sensitivity fiber-bundle array detector, a solar-blinded fiber detector and a framing camera are developed and applied to investigate the triggering characteristics of the newly designed multi-gap gas switch. Gas pressure can affect both statistical delay and formative delay. More channel arcs and smaller switch jitter are observed with the decrease in gas pressure. Trigger voltage has strong influence on statistical delay, while it has relatively small influence on formative delay and the number of channel arcs. With the UV pre-ionizing structure having a UV gap distance of 1.5-3 mm, the switch jitter can be further reduced in a large range of operating conditions.

The 5# gap sees higher breakdown voltage than the first four gaps. However, there seems to be fewer channel arcs than expected. The channel arcs do not form in line within the whole switch, and a straight discharge channel is observed in the positive charged side. The formation of channel arcs and its effect on switch inductance still need to be studied. There may be an opportunity to improve the multi-gap gas switch by controlling the stage of channel arc formation within electrode gaps.

Our research indicates that optical diagnostics is useful for understanding the underlying physics that govern the behavior of gas switches. Other optical diagnostic methods, such as time-resolved spectrum analysis, shadowgraph and interferometric imaging, can also help us to investigate the trigger characteristics of multi-gap gas switches.

References

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(Manuscript received 24 February 2013)
(Manuscript accepted 3 May 2013)
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