Electrode erosion and lifetime performance of a compact and repetitively triggered field distortion spark gap switch

Falun Song, Fei Li, Beizhen Zhang, Mingdong Zhu, Chunxia Li, Ganping Wang, Haitao Gong, Yanqing Gan, Xiao Jin, B. M. Novac, I. R. Smith

***Abstract*—Electrode erosion and lifetime performance of a compact and repetitively triggered field distortion spark gap switch was studied at a repetitive frequency rate of 30 Hz, a peak current of 8.5 kA, and working voltage of ±35 kV when the switch was filled with a gas mixture 30% SF_6 and 70% N_2 at a pressure of 0.3 MPa. The variation of the time-delay jitter and self-breakdown voltage were both studied for the whole service lifetime of the spark gap switch. The morphology of both the electrodes and the plate insulator, before and after the service lifetime tests, is also analyzed. The results show that during these tests, the time-delay jitter is basically synchronized with the self-breakdown voltage jitter, and both undergo firstly a process of rapidly decreasing their values, then remain stable and finally and gradually increase after 70,000 pulses. The change of the electrode surface roughness (i.e. the surface profile), caused by erosion and chemical deposits in the switch cavity, are mainly the two factors that affect the time-delay jitter of the switch. Tip protrusions on the electrode surface, due to electrode erosion, contribute to reducing the time-delay jitter. However, due to chemical reactions, fluorides and sulfides are deposited on the switch components, as well as metal particles caused by electrode erosion sputtering. Slowly, after a large number of shots, all these phenomena affect the self-breakdown performance resulting in an increased self-breakdown voltage jitter, which also causes the time-delay jitter to increase. Although there are a number of reasons that contribute to the performance of the switch to deteriorate it is fortunate that if a switch suffering a degraded performance is reassembled, with the electrodes mechanically polished and all the components cleaned, the optimal performance of the switch can be restored. If maintenance work is carried out regularly to preserve the condition of the switch inner components, the service lifetime of the switch can be prolonged.**

***Index Terms*—electrode erosion, service lifetime, time-delay jitter, self-breakdown voltage, micromorphology, field-distortion switch**

I. Introduction

Due to their excellent features such as high-voltage, high-current, low inductance, and low time-delay jitter, spark-gap switches are widely used in various practical applications such as particle accelerators [1], linear transformer drivers [2-3], and repetitive electron beam sources [4-5]. Recent developments in the design of repetitive pulsed power sources require spark gap switches capable of driving high-current with a low time-delay jitter (< 5 ns) and operated at a high repetition rate for a very large number of shots [6-10]. For these applications, the field-distortion switch is the optimum choice.

The performance of a spark gap switch typically deteriorates as the operational time increases. The lifetime is determined by electrode erosion, gas decomposition and disassociation and insulation damage that occurs as energy is dissipated in the switch [11]. Electrode erosion plays an important role in the many impact factors on the lifetime of the switch. Extensive research has been performed on the electrode erosion in gas switches [12-19]. Electrode erosion occurs when the electrode material is permanently removed from the electrode surface and could be considered a result of the interaction between the electrode and the arc plasma. Unfortunately, since the operating conditions vary widely from a switch design to another, there is no precise method for describing the erosion process or predicting a switch life expectancy. A systematic experimental research on electrode erosion with different electrode materials and pulse parameters have been published [20], as well as models to estimate the electrode erosion [21]. Although many researchers studied the erosion characteristics of the electrodes and evaluated the lifetime characteristics of the switches, to the authors' best knowledge, no publication covers either the processes that make the time-delay jitter and self-breakdown voltage jitter

Falun Song, Fei Li, Beizhen Zhang, Chunxia Li, Ganping Wang, Haitao Gong, Yanqing Gan and Xiao Jin, are with Science and Technology on High Power Microwave Laboratory, Institute of Applied Electronics, China Academy of Engineering Physics, Mianyang 621900, China (email: songfalun@caep.cn; shanxilifei@163.com; 99477228@qq.com; lichunxia@tsinghua.org.cn; wanggpcaep@163.com; 2712019073@qq.com; emplasma@tom.com; Xiao_jin@hotmail.com). (*Corresponding author*: *Falun Song*).

B. M. Novac and I. R. Smith are with Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom (email: B.M.Novac@lboro.ac.uk; I.R.Smith@lboro.ac.uk).

Mingdong Zhu is with China State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China (email: zhumingdong2008@163.com)

vary with the lifetime, or on how and when to carry out appropriate maintenance work. This paper reports on studies of electrode erosion and lifetime performance of a compact and repetitively triggered field distortion spark gap switch. The main factors affecting the performance of the switch are analyzed and a schedule for preventive maintenance work is suggested to provide the basis for further prolonging the service lifetime of a spark-gap switch.

II. EXPERIMENTAL ARRANGEMENT

A compact three-electrode field-distortion spark gap switch was used, which includes two main electrodes, two plate insulators of Polymethyl methacrylate (PMMA), a disk-like trigger electrode, two pairs of O-ring seals and sixteen nylon screws for fastening. The main electrodes and trigger electrode are made of 316L stainless steel. The switch has a small size (OD × height) of only 150 mm × 42 mm, a light weight of about 1.5 kg, can withstand a high voltage in excess of 110 kV. Fig. 1 provides a schematic overview of the experimental arrangement used in the present studies. This paper is a follow-on of [22], with the technical details and experimental arrangement being fully described therein.

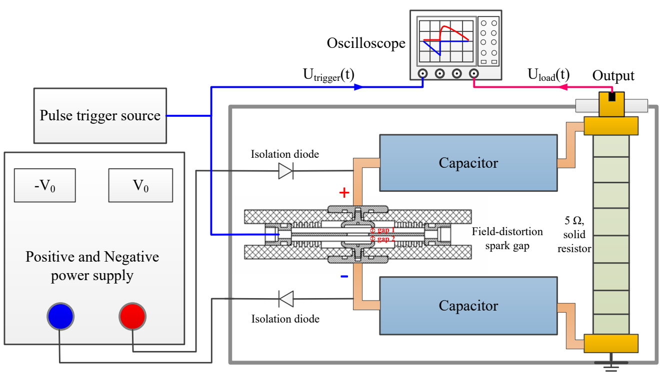

Fig. 1. Schematic of the experimental arrangement used in the present studies.

III. Experimental results and discussion

A. Degradation of switch performance

Time-delay jitter is an important parameter in describing the quality of synchronization between switches operated in parallel and can greatly influence the rise time of the final output current of the system: a too large value will slow down the energy transfer rate. The self-breakdown of the switch refers to the phenomena that occur when the applied voltage exceeds the maximum withstand voltage. The self-breakdown voltage affects the operating voltage range, which is an important parameter for a triggered switch. To study the performance degradation of the present switch, the time-delay jitter and the self-breakdown voltage were both measured during the lifetime tests, as shown in Fig. 2. For these tests, a new switch was used, which was filled with the SF_6-N_2 gas mixture at a pressure of 0.3 MPa, the applied voltage was ±35 kV, and the current was 8.5 kA, and a trigger pulse with a voltage time rate-of-change of 0.25 kV/ns was used. Due to residual burrs and incompletely cleaned stains remaining on the surface of the electrodes after they were manufactured, the breakdown voltage varied greatly during the first 100 shots of switch 'forming', so the operation frequency was set to 1Hz during this preliminary part of the test. After forming, the switch was operated at a repetition-rate of 30 Hz, since it was demonstrated that the optimum repetition frequency that minimizes the time-delay jitter is in a range between 20 Hz and 30 Hz, when the spark gap is filled with a gas mixture of 30% SF_6 and 70% N_2 [24].

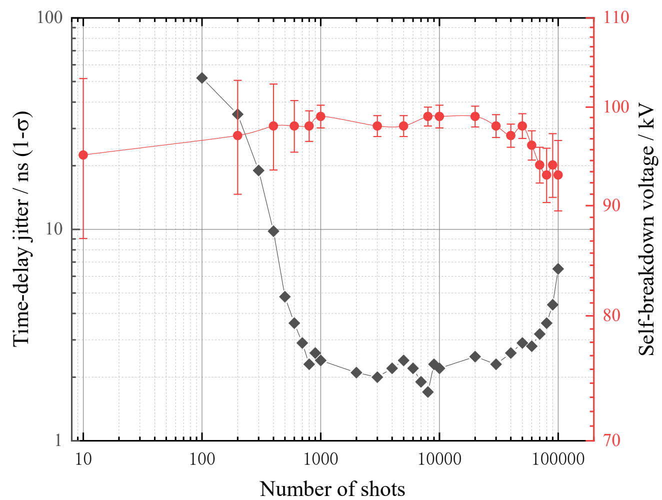

Fig. 2. Time-delay jitter and self-breakdown voltage versus the number of pulse shots for a new switch.

Tests results show that the time-delay jitter is rapidly reduced within the first 700 shots. For the next 60,000 shots, the time-delay jitter is practically stable having values between 1.7 ns and 3.0 ns. However, from about 70,000 shots to 100,000 shots, the time-delay jitter increases from 3.2 ns to 6.5 ns. The self-breakdown voltage jitter also appears to be a process that initially decrease rapidly before remaining stable for the long lifetime of about 70000 shots after which it is gradually degrading, in a similar way as the time-delay jitter. When the time-delay jitter is large, the self-breakdown voltage jitter is also large. When the time-delay jitter is low, the self-breakdown voltage jitter is also relatively small. The reasons for this phenomenon are related to the electrode erosion and the chemical composition within the switch resulting from the gas discharge, both of which are discussed in detail below.

B. The complex phenomena of electrode erosion and their influence on the switch lifetime

Fig. 3 presents photographs of the main switch components: the trigger electrode, the plate insulator and the main electrode, after 100,000 shots. It can be seen that an annular erosion region is formed on the trigger electrode, with a diameter similar to that of the main electrode. This annular region is evenly eroded, which is an important indication suggesting a stable operation. However, there are many tiny cracks, pits and bumps on both the main electrode and the trigger electrode surface and also a layer of white powder attached to the surfaces of both the electrode and the plate insulator. The appearance of all these unwanted phenomena may provide the explanation of why the time-delay jitter gradually increases after 70,000 shots. In order to fully understand the nature of these phenomena, the microstructure of the main electrode and the trigger electrode were all analyzed before, during and after the tests, with the main results presented in Fig. 4.

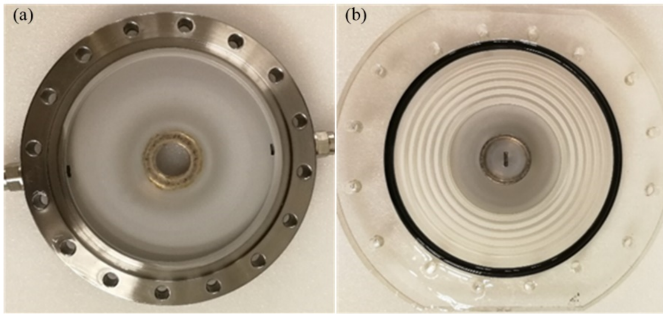

Fig. 3. Photographs of certain switch components after 100,000 shots. (a) trigger electrode and (b) plate insulator and the main electrode.

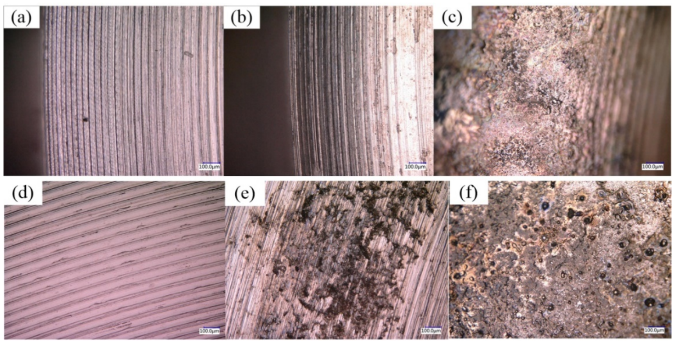

Fig. 4. The change in the micromorphology of the main and the trigger electrode from 0 shots to 100,000 shots. (a) initial state of the main electrode surface. (b) main electrode surface after 1,000 shots. (c) main electrode surface after 100,000 shots. (d) initial state of the trigger electrode surface. (e) trigger electrode surface after 1,000 shots. (f) trigger electrode surface after 100,000 shots.

The time-delay jitter degradation due to the electrode profile change caused by erosion can be explained by the comparation of the micromorphology of the electrodes when tested at different number of pulse shots, as shown in Fig. 4. After 1000-shot tests, the surface of the trigger electrode opposite to the positive electrode became rough with a large number of tip protrusions (see Fig. 4(e)), which promoted the generation of initial electrons and facilitated breakdown of the switch, resulting in much lower time delay jitter. This explanation is supported by other published works [25, 26].

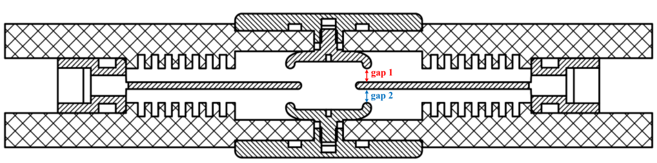

Fig. 5. Schematic of the three-electrode spark gap switch used in the present studies.

Due to the presence of the disk-like trigger electrode, the space between the two electrodes of the switch described in this paper is divided into two equal parts: 'gap 1' and 'gap 2', as shown in Fig. 5. Gap 1 represents the triggered gap while gap 2 is the self-breakdown gap. Results presented in [24]. show that, for a trigger pulse having a voltage/time rate-of-change 0.25 kV/ns and when the working coefficient of the switch exceeds 0.7, the time-delay jitter is dominated by gap 1, where the working coefficient is the ratio of operating voltage to self-breakdown voltage. The presence of tip protrusions on the trigger or main electrode is beneficial to reducing the time-delay jitter of gap 1. However, as the number of test shots increases, the protrusions on the surface of the electrode become relatively uniform and smooth under the constant erosion and melting due to arc discharge (see Fig. 4(f)). As described earlier, when the number of test shots is greater than 70,000, the time-delay jitter of the switch starts to gradually increase with the shot number, which indicates the electrode surface erosion gradually became uniform and smooth.

Experimental results show that moderate erosion of the electrodes is beneficial in reducing the time-delay jitter of the switch, but excessive erosion increases the time-delay jitter. It can be predicted that there is an optimum electrode surface profile that minimizes the time-delay jitter.

C. Element Spectrum Analysis

As evident in Fig. 6, a layer of white powder covers the surfaces of the main electrodes, the trigger electrode and the plate insulator. The chemical composition of this powder was analyzed using X-ray photoelectron spectroscopy (XPS) before and after tests, with the main results presented in Fig. 7 and Fig. 8. It can be seen from Fig. 7 that peaks of elements such as S, N and F are clearly present when the surface of the insulator is analyzed after a large number of high-frequency operations. The F element is also detected in the white powder on the surface outside the discharge region of the trigger electrode, as shown in Fig. 8. Further analysis indicates that gases, such as CO_2, CO, CF_4 and H_2S were also generated during the discharges. An unexpected, but very important finding is the presence of metallic elements such as Fe and Mo on the surface of the insulator, which may cause its insulation performance to deteriorate quickly.

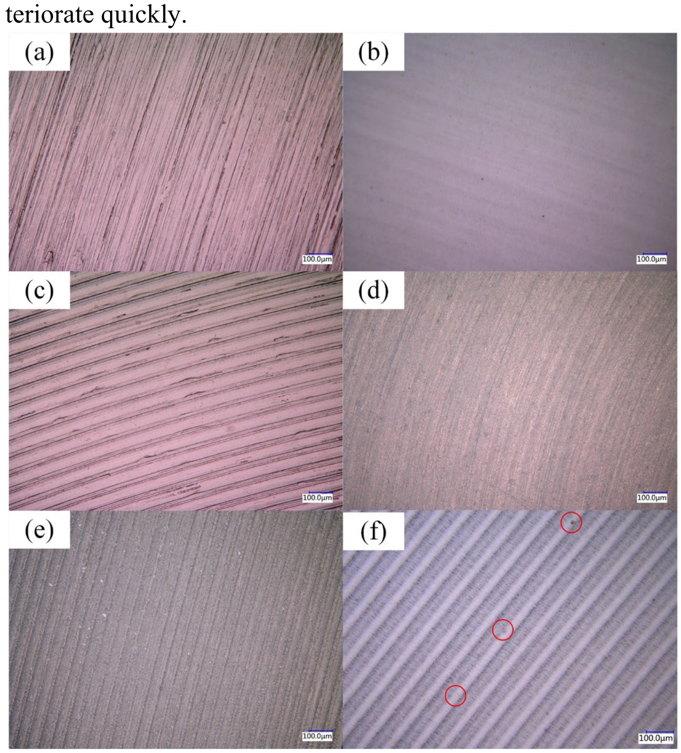

Fig. 6. Change in the micromorphology of various switch components from 0 shots to 100,000 shots. (a) initial state of the trigger electrode surface outside of the discharge area. (b) the trigger electrode surface outside of the discharge area after 100,000 shots. (c) initial state within the main electrode. (d) the surface within the main electrode after 100,000 shots. (e) initial state of the first annular surface on the plate insulator. (f) the first annular surface on the plate insulator after 100,000 shots; the position of a few metallic micro particles adhered to the insulator surface is highlighted using circles.

On the surface of the plate insulator there are some 10 μm-sized sputtered metal spots, as seen in Fig. 6(f), which proves

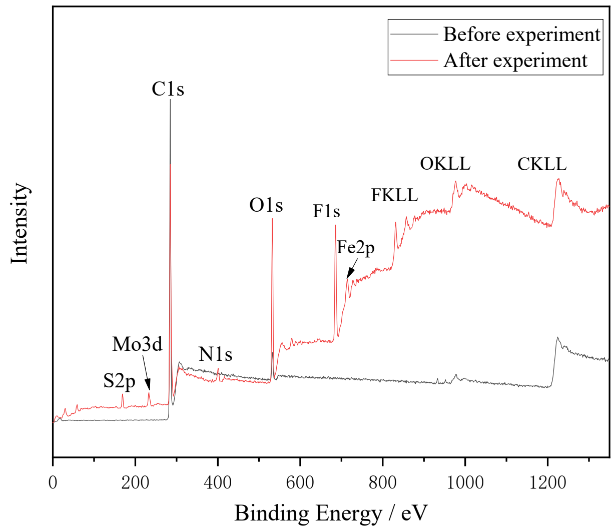

Fig. 7. The full XPS spectrum of the white powder present on the plate PMMA insulator surface after 100,000 shots, compared with the initial spectrum obtained before the tests.

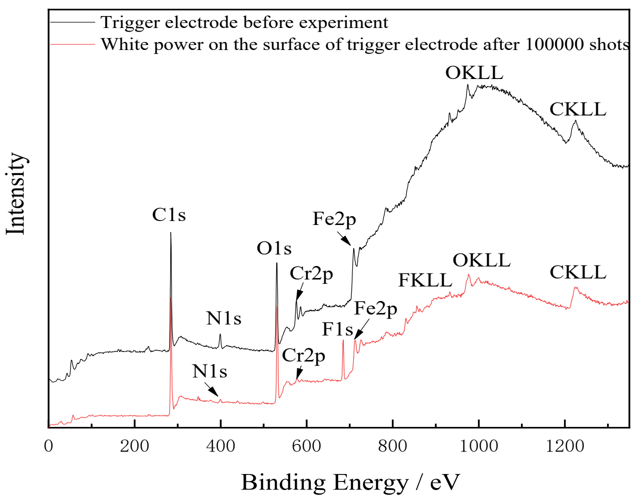

Fig. 8. The full XPS spectrum of the white powder present on the trigger electrode surface outside the discharge area after 100,000 shots compared with the initial spectrum obtained before the tests.

that melted electrode material near the electric arc spot was ejected during the high frequency operation. These metallic micro particles adhered to the surface of the plate insulator, obviously decreasing its insulation properties and leading to an overall reduction in the lifetime of the switch.

The presence of fluorides, sulfides and metal particles inside the switch cavity after a certain number of shots can also affect the discharge performance, causing the time-delay jitter to gradually increase and the insulation performance to deteriorate.

D. *Partial discharge and its influence on the switch lifetime*

In addition to electrode erosion, another important factor that affects the lifetime of the switch is the partial discharge, which can create localized breakdown and permanent damage to the insulating material. As the number of pulse discharges increases, the breakdown of the insulating material caused by partial discharge will gradually expand, eventually leading to complete body-breakdown, resulting in failure of insulation performance and preventing the switch from working.

For the compact field-distortion spark gap switch described in this paper, the triple-point of the high-voltage main electrode, the insulating gas, and the plate insulator is the place where the partial discharge is most likely to occur, so it is necessary to minimize the electric field strength by careful design. The main electrode shown in Fig. 9(a) has a sharp edge which greatly enhances the electric field strength. As shown in Fig. 9(a), after 100,000 shots tests with this main electrode design, the plate insulator had obvious dendritic breakdown marks as presented in Fig. 10. This damage is critical and cannot be recovered, thus affecting the service lifetime of the switch. This phenomenon can be however avoided if the sharp edge of the electrode is rounded as presented in Fig. 9(b)). A careful structural design to avoid partial discharges is therefore important for improving the lifetime of the switch.

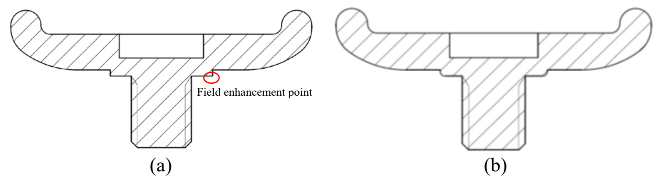

Fig. 9. The main electrode of the switch before and after the sharp edge was rounded.

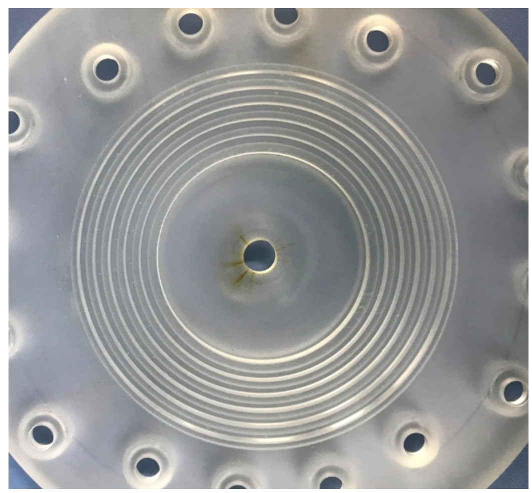

Fig. 10. Photo of a plate insulator after 100,000 shots test using the main electrode with sharp edge.

E. *Switch performance recovery*

To further understand the specific reasons for the observed deterioration in the switching performance after 100,000 shots of the lifetime tests, the switch was disassembled and an ultrasonic cleaner was used to clear all attachments from the surfaces of the main electrodes, trigger electrode and plate insulators. After that, the following five experiments were conducted for different component combinations of the switch, as shown in Table I.

Switch I. The main and trigger electrodes are brand new; The plate insulators are old but cleaned.

Switch II. The main and trigger electrodes are old and cleaned, but the plate insulators are brand new.

Switch III. The main electrodes, trigger electrode and plate insulators are all old and cleaned.

Switch IV. The main and trigger electrodes are old but had been mechanically polished and cleaned. The plate insulators are also old but cleaned.

Tab. I. Comparison of five different component combinations of the switch

	Switch I		**Switch II**		**Switch III**		**Switch IV**		**Switch V**		**Switch 0**
components	**Main electrodes**	new	**Main electrodes**	old, cleaned	**Main electrodes**	old, cleaned	**Main electrodes**	old, cleaned, polished	**Main electrodes**	old, cleaned, polished	Final state after 100,000 shot tests.
	Trigger electrode	new	**Trigger electrode**	old, cleaned	**Trigger electrode**	old, cleaned	**Trigger electrode**	old, cleaned, polished	**Trigger electrode**	old, cleaned, polished	
	Plate insulators	old, cleaned	**Plate insulators**	new	**Plate insulators**	old, cleaned	**Plate insulators**	old, cleaned	**Plate insulators**	new	
"forming" shots	1000		1000		1000		1000		1000		---
average delay time	170 ns		183 ns		181 ns		186 ns		189 ns		178 ns
time-delay jitter	2.4 ns		4.5 ns		4.7 ns		2.7 ns		2.8 ns		6.5 ns

Switch V. The main and trigger electrodes are old but had been mechanically polished and cleaned. The plate insulators are brand new.

Switch 0. The final state after 100,000-shot tests.

As the data in Table I shows, if new main and trigger electrodes are used in reassembling the switch with old but cleaned insulators (Switch I), the switch has the essentially the same time-delay jitter (~2.4 ns) as the new one (used in Fig. 1). After cleaning the attachments inside the switch, the time-delay jitter is reduced from 6.5 ns (Switch 0) to 4.7 ns (Switch III). Compared to Switch III, by replacing new plate insulators, the time-delay jitter of Switch II (4.5 ns) is not changed. Within the allowed deviation range, the time-delay jitters of Switch II and Switch III are considered to be practically the same. However, when the main electrodes and the trigger electrode of the switch were mechanically polished and cleaned, the time-delay jitter is further reduced to 2.7 ns (Switch IV). Compared to Switch IV, the time-delay jitter of Switch V (2.8 ns) is not changed by replacing new plate insulators.

The experimental results of Switch II and Switch III show that if only the chemical deposits caused by the discharge in the switch cavity are cleaned, the time-delay jitter cannot be restored to the optimal state, which means that the deposits of chemical reaction are a factor affecting the time-delay jitter, but not the only factor.

The experimental results of Switch IV and Switch V show that the surface roughness of the electrode (i.e. the surface profile) has a great influence on the time-delay jitter. After the surface of the electrode is mechanically polished, the surface profiles of the electrodes are substantially the same as that of the new electrode. Therefore, with the component combinations such as Switch IV and Switch V, the time-delay jitter of the switch can be restored to its optimal state.

Fortunately, the experimental results of Switch IV further indicate that if after 100,000 shots of the lifetime tests the main and the trigger electrode of the switch are both mechanically polished and cleaned and then reassembled with the cleaned old plate insulators, the time-delay jitter of the switch can still be restored to its optimal state. This provides an experimental basis for the switch maintenance and recovery.

IV. CONCLUSION

In this paper, electrode erosion and lifetime performance of a compact and repetitively triggered field distortion spark gap switch was studied and the main factors affecting the performance of the switch were analyzed in detail. The experimental results show that the electrode surface roughness (i.e. the surface profile) and chemical deposits caused by discharge are two main factors affecting the time-delay jitter of the switch. Fluoride, sulfide and metal particles that are present inside the switch cavity, as well as damage to the insulator due to partial discharge, are also important factors influencing the lifetime of the switch. By optimizing the electrode surface profile design and avoiding partial discharge, the lifetime of the switch insulator can be improved. By periodically carrying work to preserve the state of the switch components, the service lifetime of the switch can be prolonged.

Future plans include increasing the operation lifetime of the switch by using a better erosion-resistant electrode material such as a copper-tungsten alloy and decreasing the time-delay jitter of the switch by optimizing the electrode surface profile in the discharge region.

REFERENCES

[1] X. D. Liu, X. F. Jiang, F. J. Sun, T. X. Liang, Q. G. Zhang and A. C. Qiu, "Experimental study on synchronous discharge of ten multigap multichannel gas switches," IEEE Trans. Plasma Sci., vol. 37, no. 10, pp. 1943-1947, Oct. 2009.

[2] M. G. Mazarakis, W. E. Fowler, K. L. LeChien, F. W. Long, M. K. Matzen, D. H. McDaniel, R. G. McKee, C. L. Olson, J. L. Porter, S. T. Rogowski, K. W. Struve, W. A. Stygar, J. R. Woodworth, A. A. Kim, V. A. Sinebryukhov, R. M. Gilgenbach, M. R. Gomez, D. M. French, Y. Y. Lau, J. C. Zier, D. M. VanDevalde, R. A. Sharpe and K. Ward, "High-current linear transformer driver development at Sandia National Laboratories," IEEE Trans. Plasma Sci., vol. 38, no. 4, pp. 704-713, April 2010.

[3] A. A. Kim, B. M. Kovalchuk, V. A. Kokshenev, A. V. Shishlov, N. A. Ratakhin, V. I. Oreshkin, V. V. Rostov, V. I. Koshelev and V. F. Losev, "Review of high-power pulsed systems at Institute of High Current Electronics," Matter and Radiation at Extremes, vol. 1, pp. 201-206, 2016.

[4] F. L. Song, F. Li, B. Z. Zhang, H. T. Gong, Y. Q. Gan and X. Jin, "A compact low jitter high power repetitive long-pulse relativistic electron beam source," Nucl. Instrum. Methods Phys. Res. A, vol. 919, pp. 56-63, 2019.

[5] F. L. Song, F. Li, B. Z. Zhang, M. D. Zhu, C. X. Li, G. P. Wang, H. T. Gong, Y. Q. Gan and X. Jin, "Recent advances in compact repetitive high-

power Marx generators," Laser and Particle Beams, vol. 37, pp. 110-121, 2019.

[6] J. A. Gaudet, R. J. Barker, C. J. Buchenauer, C. Christodoulou, J. Dickens, M. A. Gundersen, R. P. Joshi, H. G. Krompholz, J. F. Kolb, A. Kuthi, M. Laroussi, A. Neuber, W. Nunnally, E. Schamiloglu, K. H. Schoenbach, J. S. Tyo and R. J. Vidmar, "Research issues in developing compact pulsed power for high peak power applications on mobile platforms," Proceedings of the IEEE, vol. 92, no. 7, pp. 1144-1165, July 2004.

[7] J. R. Woodworth, J. A. Alexander, F. R. Gruner, W. A. Stygar, M. J. Harden, J. R. Blickem, G. J. Dension, F. E. White, L. M. Lucero, H. D. Anderson, L. F. Bennett, S. F. Glover, D. Van DeValde and M. G. Mazarakis, "Low-inductance gas switches for linear transformer drivers," Phys. Rev. ST Accel. Beams, **12**, 060401, 2009.

[8] J. R. Woodworth, W. A. Stygar, L. F. bennett, M. G. Mazarakis, H. D. Anderson, M. J. Harden, J. R. Blickem, F. R. Gruner and R. White, "New low inductance gas switches for linear transformer drivers," Phys. Rev. ST Accel. Beams, **13**, 080401, 2010.

[9] X. B. Cheng, J. L. Liu, B. L. Qian, Z. Chen and J. H. Feng, "Research of a high-current repetitive triggered spark-gap switch and its application," IEEE Trans. Plasma Sci., vol. 38, no. 3, pp.516-522, Mar. 2010.

[10] G. J. J. Winands, Z. Liu, A. J. M. Pemen, E. J. M. Van Heesch and K. Yan, "Long lifetime, triggered, spark-gap switch for repetitive pulsed power application," Rev. Sci. Instrum., vol. 76, 085107, 2005.

[11] A. L. Donaldson, M. O. Hagler, M. Kristiansen, G. Jackson and L. Hatfield, "Electrode erosion phenomena in a high-energy pulsed discharge," IEEE Trans. Plasma Sci., vol. PS-12, no. 1, pp.28-38, Mar. 1984.

[12] J. W. Wu, R. Y. Han, W. D. Ding, H. B. Zhou, Y. F. Liu, Q. J. Liu, Y. Jing and A. C. Qiu, "Electrode erosion characteristics of repetitive long-life gas spark switch under airtight conditions," IEEE Trans. Plasma Sci., vol. 43, no. 10, pp. 3425-3433, Oct. 2015.

[13] Y. Liu, Z. Y. Li, Q. P. Luo, Y. B. Han, Q. Zhang and F. C. Lin, "Comparison and evaluation of electrode erosion under high-pulsed current discharges in air and water mediums," IEEE Trans. Plasma Sci., vol. 44, no. 7, pp. 1169-1177, July 2016.

[14] J. M. Koutsoubis and S. J. MacGregor, "Electrode erosion and lifetime performance of a high repetition rate, triggered, corona-stabilized switch in air," J. Phys. D: Appl. Phys., vol. 33, pp. 1093-1103, 2000.

[15] X. A. Li, X. D. Liu, X. Q. Gou, F. H. Zeng and Q. G. Zhang, "Degradation of performance due to electrode erosion in field distortion gas switch in long-term repetitive operation," IEEE Trans. Plasma Sci., vol. 42, no. 10, pp. 3064-3069, Oct. 2014.

[16] V. Nemchinsky, "Cathode erosion in a high-pressure high-current arc: calculations for tungsten cathode in a free-burning argon arc," J. Phys. D: Appl. Phys., vol. 45, 135201, 2012.

[17] P. D. Kumar, S. Kumar, R. Thakur, A. Upadhyay and T. Raychaudhuri, "Erosion and lifetime evaluation of Molybdenum electrode under high energy impulse current," IEEE Trans. Plasma Sci., vol. 39, no. 4, pp. 1180-1186, April 2011.

[18] X. D. Liu, H. Wang, X. A. Li, Q. G. Zhang, J. Wei, A. C. Qiu, "Estimation of surface roughness due to electrode erosion in field-distortion gas switch," Plasma Sci. Technol. vol. 15, no.8, pp. 812-816, Aug. 2013.

[19] L. B. Gordon, M. Kristiansen, M. O. Hagler, H. C. Kirbie, R. M. Ness, L. L. Hatfield and J. N. Marx, "Material studies in a high energy spark gap," IEEE Trans. Plasma Sci., vol. PS-10, no. 4, pp.286-293, Dec. 1982.

[20] A. L. Donaldson, *Electrode Erosion in High-Current, High-Energy transient Arcs*. Lubbock, TX, USA: Texas Tech Univ, 1991.

[21] A. Watson, A. L. Donaldson, K. Ikuta and M. Kristiansen, "Mechanism of electrode surface damage and material removal in high current discharge," IEEE Trans. Magn., vol. MAG-22, no. 6, pp. 1799-1803, Nov. 1986.

[22] F. L. Song, F. Li, B. Z. Zhang, M. D. Zhu, C. X. Li, G. P. Wang, H. T. Gong, Y. Q. Gan, X. Jin, B. M. Novac and I. R. Smith, "Compact and Repetitively Triggered, Field-distortion Low-jitter Spark-gap Switch," IEEE Trans. Plasma Sci., manuscript under consideration.

[23] J. R. Woodworth, J. A. Alexander, F. R. Gruner, W. A. Stygar, M. J. Harden, J. R. Blickem, G. J. Dension, F. E. White, L. M. Lucero, H. D. Anderson, L. F. Bennett, S. F. Glover, D. Van DeValde and M. G. Mazarakis, "Low-inductance gas switches for linear transformer drivers," Phys. Rev. ST Accel. Beams, **12**, 060401, 2009.

[24] F. L. Song, F. Li, B. Z. Zhang, M. D. Zhu, C. X. Li, G. P. Wang, H. T. Gong, Y. Q. Gan, X. Jin, B. M. Novac and I. R. Smith, "Analysis of the optimal operation frequency with lowest time-delay jitter for an electrically triggered field-distortion spark gap," IEEE Trans. Plasma Sci., manuscript under consideration.

[25] J. Y. Geng, J. H. Yang, X. B. Cheng, X. Yang and R. Chen, "The development of high-voltage repetitive low-jitter corona stabilized triggered switch," Rev. Sci. Instrum., **89**, 044705, 2018.

[26] A. Pedersen, "The effect of surface roughness on breakdown in SF_6," IEEE Trans. Power Apparatus and systems, vol. PAS-94, no. 5, pp. 1749-1754, September/October 1975.

Falun Song was born in Shandong, China, in 1977. He received the B.S. degree from Liaocheng Normal University, Liaocheng, China, in 2000, and the Ph.D. degree from the University of Science and Technology of China, Anhui, China, in 2005.

He is currently an Associate Professor with the Institute of Applied Electronics, China Academy of Engineering Physics, Mianyang, China. He is also an Academic Visitor with Loughborough University, UK. He is involved in pulsed-power and plasma immersion ion implantation technology.

Fei Li was born in Shanxi, China in 1987. He received the B.S. degree and the Ph.D. degree from Lanzhou University, Lanzhou, China, in 2009 and 2014, respectively. His current research interests include pulsed power technology and material surface treatment technology.

Beizhen Zhang was born in Heilongjiang, China, in 1982. He received the B.S. degree from Jilin University, Jilin, China, in 2005. His current research interests include pulsed power technology and mechanical structural design.

Chunxia Li was born in Sichuan, China, in 1983. She received the B.S. degree from Tsinghua University, Beijing, China, in 2005. Her research interests include pulsed power technology and electron beam diagnostic technology.

Ganping Wang was born in Shandong, China, in 1983. He received the B.S. degree from the University of Science and Technology of Xi'an, Xi'an, China, in 2005, and the M.S. degree in physics of wireless electronics from the Graduate school of China Academy of Engineering Physics (CAEP), Beijing, China, in 2009. He is currently pursuing the Ph.D. degree in physics of Wireless Electronics with the Graduate school of CAEP. His research interests include high-power pulsed power technology.

Haitao Gong was born in Sichuan, China, in 1973. He is a skilled worker who has been engaged in research on the pulsed power sources for more than 23 years.

Yanqing Gan was born in Gansu, China, in 1970. He has been engaged in research on pulsed-power sources for more than 27 years. He is currently involved in pulsed-power measurement technology and plasma diagnostic technology.

Xiao Jin was born in Zhejiang, China, in 1969. He received the B.S. degree from Tsinghua University, Beijing, China, in 1992, and the Ph.D. degree from the Graduate School of China Academy of Engineering Physics, Beijing, in 2002.
In 2006, he was a professor with the Institute of Applied Electronics, China Academy of Engineering Physics. His current research interests include pulsed-power technology, high-power microwave technology, and free-electron laser technology.

Mingdong Zhu was born in Sichuan province, China, in 1989. He received the B. S. and M. S. degrees from the Harbin Institute of Technology (HIT), Harbin, China, in 2011 and 2014, respectively. He is currently pursuing the Ph. D. degree with the China State Key Laboratory of Advanced Welding and Joining, HIT. He has been working on plasma immersion ion implantation technology.

Bucur M. Novac (M'06 – SM'08) received the M.Sc. and Ph.D. degrees in 1977 and 1989, respectively, both from the University of Bucharest. He joined the Loughborough University, UK in 1998 and is currently Professor of Pulsed Power. His research interests include compact and repetitive high-power systems, explosively and electromagnetically driven magnetic flux compression generators and their applications, electromagnetic launchers, ultrafast magneto and electro-optic sensors and 2-D modeling of pulsed-power systems. He has co-authored two books on explosive pulsed power and has published more than 200 refereed papers and conference contributions.
Prof. Novac is a voting member of the Pulsed Power Science & Technology Committee in the IEEE Nuclear and Plasma Science Society. He is also a member of the International Steering Committees for both the MEGAGAUSS Conferences and for the Euro-Asian Pulsed Power Conferences. He is also member of the organizing committee for the IEEE International Power Modulator and High Voltage Conference and co-chairman of the UK Pulsed Power Symposium. Prof. Novac is a Chartered Engineer a Fellow of the Royal Academy of Engineering and of the Institution of Engineering and Technology (IET), UK.

Ivor R. Smith received the B.Sc. and Ph.D. degrees from the University of Bristol, Bristol, U.K., after completing a student apprenticeship at the Witton Works of the General Electric Company, and the D.Sc. degree from the University of Birmingham, Birmingham, U.K., for his continued research contribution. He was a Lecturer in electrical engineering with the University of Birmingham and was subsequently promoted to Lecturer and Reader. He then moved to Loughborough University, Leicestershire, U.K., as a Professor of electrical power engineering and served as the Head of Department, Dean of Engineering, and Pro-Vice Chancellor. He has been active in research in many aspects of the production, conditioning, and utilization of large pulses of electrical energy, and his work has brought in very substantial funding from a wide range of sponsors. Dr. Smith is a Chartered Engineer, a Fellow of the Institution of Engineering and Technology and the Royal Academy of Engineering.