Analysis of the optimal operation frequency with lowest time-delay jitter for an electrically triggered field-distortion spark gap

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*—The present work was stimulated by the assumption that, for a gas-filled spark gap closing switch operating at a high repetition frequency, there is an optimal frequency range in which the time-delay jitter is reaching a minimum value. The experiments to test this assumption use an electrically triggered, field-distortion spark gap filled with SF_6/N_2 gas mixture. The results show that indeed, the time-delay jitter decreases for a range of frequencies for which the filling gas can substantially restore the inter-electrode insulation, before increasing at a higher operation frequency. The experimental results demonstrate the correctness of the above presented assumption: the time-delay jitter of the field-distortion spark gap has its minimum when the unit operates in the repetition frequency range between 20 Hz and 30 Hz. Since the recovery time depends on gas species and gap distance, the optimum operation frequency range should also vary depending on the spark gap distance and the filling gas properties.**

***Index Terms*—optimal repetition frequency, low time-delay jitter, field distortion, spark gap switch**

I. Introduction

Due to their excellent features such as high-voltage, high-current, low inductance, and high di/dt rate, spark gap switches are widely used in various practical applications such as particle accelerators, weapon effect simulation, controlled thermonuclear fusion, high-power lasers, and high-power microwaves [1]. 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 (~100 Hz) for a very large number of shots [2-6]. The low time-delay jitter characteristics at a high value of repetition frequency is a critical parameter, in particular when a large number of switches are required to function synchronously as part of parallel-operated pulsed power sources. The main issues related to high repetition-rate operation of spark gaps are mainly related to electrode heat and mass transfer, gas deionization and recombination and other electrode material phenomena. Investigations into the repetitive operation of spark gaps have led to some degree of understanding of the nature of gas recovery processes [7-8]. The time-delay jitter of the switch, defined as the time-delay standard deviation,

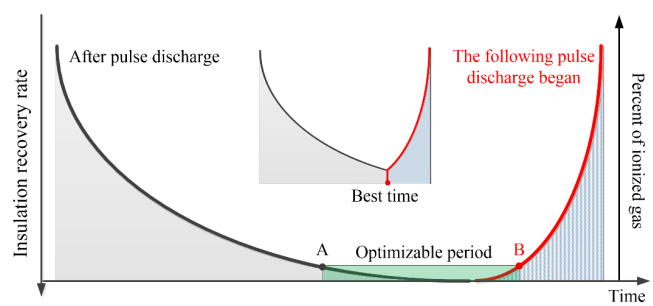


Fig. 1. Schematic diagram of the 'optimizable time period' between two consecutive discharges. Point A is the time at which the insulation properties of the gas are substantially restored and when the switch works stably if a following pulse discharge is trigger initiated. At point B, the gap is filled with 'seed' electrons, which will cause an electron avalanche.

is a fundamental characteristic in the development and evaluation of spark gaps for major practical applications [9-12]. The main factors affecting the time-delay jitter of a triggered spark gap are the statistical time delay for generating free electrons, the electric field applied across the electrodes and the trigger pulse rise time [13].

On the one hand, the gas insulation recovery time is of the

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)

order of a few tens of milliseconds during which, due to the existence of residual electrons, the gas is more easily ionized. On the other hand, the presence of these residual electrons (also possibly termed 'initial' or 'seed' electrons) in the spark gap gas helps reducing the breakdown time-delay, thereby reducing the time-delay jitter. Based on the above two aspects, it is natural to assume *there is an optimal repetition frequency range for which the time-delay jitter of the switch reaches a minimum value* and Fig. 1 shows a schematic diagram presenting this assumed 'optimizable time period' between two consecutive discharges. Since the recovery time depends on gas species and gap distance [14-18], the optimum operation frequency range should also vary depending on the spark gap distances and the filling gas properties. In [19], experimental results presented that there is a lowest jitter for an 81% H_2 and 19% N_2 gas mixture and the pure H_2 gas when operate at a repetition rate, but they did not give a specific reason.

In this paper, the time-delay jitter characteristics of an electrically triggered three-electrode field distortion spark gap is experimentally analyzed in repetitive mode operation to find the optimal operation frequency with the lowest jitter. The results of the study are believed to lay the foundations for the development of a powerful, low-jitter repetitive pulsed power source.

II. EXPERIMENTAL ARRANGEMENT

Fig. 2 provides a schematic overview of the experimental arrangement used in the present studies. A compact three-electrode field-distortion spark gap switch was used, which has a small size (OD × height) of only 150 mm × 42 mm, a light

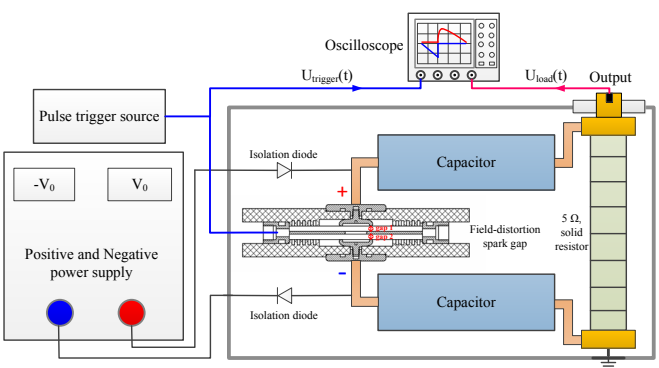


Fig. 2. Schematic of the experimental arrangement used in the present studies.

weight of about 1.5 kg, and can withstand a high voltage in excess of 110 kV. The technical details for this switch have been provided elsewhere [20]. Due to the presence of the disk-like trigger electrode, the 8 mm space between the two electrodes of the switch is divided into *two equal parts*: 'gap 1' and 'gap 2' (see the central part of the switch in Fig. 2).

The arrangement uses a test stand similar to that of a single Linear Transformer Driver (LTD) brick [21] i.e., two 100 kV/35 nF capacitors form an energy storage component using a single closing switch. The total loop circuit self-inductance is only 220 nH and when the switch operates at ± 35 kV a peak current of 8.5 kA is generated.

A dual polarity (i.e., positive and negative) power supply, with a maximum output voltage of ±60 kV is used to charge the capacitors for a maximum repetition frequency operation of 200 Hz. Three different trigger pulses with voltage/time change rates of 0.03 kV/ns, 0.25 kV/ns and 1.0 kV/ns are used to study the effect of the rise time of the trigger pulse on the time-delay jitter. Two high-voltage probes type EP-150k NEP with upgraded bandwidth 75 MHz are used to measure the trigger pulse voltage and the transient voltage applied on the load and a digital oscilloscope type Lecroy HDO 6054 with bandwidth 500 MHz is used to record the data.

Following [22] a 30% SF_6 to 70% N_2 gas mixture is used to fill the switch, as it has better stabilization characteristics than pure SF_6 or N_2 and can be triggered more easily over a wider pressure range.

Fig. 3 shows the typical waveforms for the trigger pulse voltage and for the voltage pulse applied to the load, with the breakdown time delay measured from the time the trigger pulse is applied to the moment the switch is fully closed. When the trigger pulse is

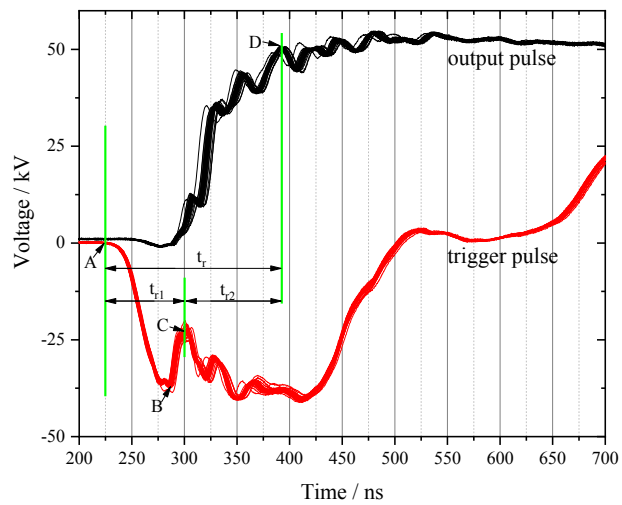


Fig. 3. Waveforms of the trigger pulse voltage (lower trace) and of the output pulse i.e., the voltage applied to the load (upper trace). t_{r1} and t_{r2} are the time delays for gap 1 and gap 2, respectively; t_r represents the overall time-delay of the spark gap switch. Time A: trigger pulse applied; time B: the impedance of gap 1 starts to collapse; time C: the impedance of gap 2 starts to collapse; time D: the channel formed.

applied, gap 1 closes quickly and the voltage on the trigger electrode becomes the sum of the positive electrode voltage and the trigger voltage, causing the self-breakdown closure of gap 2. The time-delay jitter of the switch during repetitive operation is obtained by measuring all the values of t_r and calculating the corresponding standard deviation.

III. RESULTS AND ANALYSIS

Fig. 4 presents the variation of the system time-delay jitter when the arrangement is operated at various repetition frequencies, with the spark gap switch filled with a SF_6-N_2 gas mixture at a pressure of 0.25 MPa and the switch is triggered with a voltage impulse having a time rate-of-change of 0.25 kV/ns. The data obtained proves that when the switch operates at a repetition rate less than 50 Hz, the time-delay jitter is very stable and reduces to less than 2.0 ns for a working coefficient larger than 0.77, where the working coefficient is the ratio of the applied voltage across the switch to the self-breakdown voltage. However, when the repetition frequency is higher than 100 Hz, the time-delay jitter increases rapidly and the switch operation becomes unstable, the dispersion of the time-delay jitter

becomes larger as shown by the error bars in Fig. 4. The explanation for this phenomenon is that a too high repetition rate frequency produces an increased Joule (heat) effect and under such conditions the dynamics of the gas components in the switch cavity do not allow recovering its normal initial state, as required for a stable operation. In other words, the tests proved that it takes more than 10 ms for the gas to recover to its stable initial conditions.

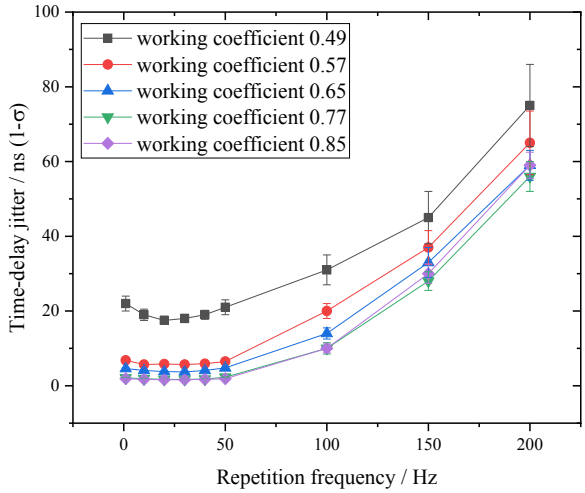


Fig. 4. Variation of time-delay jitter with repetition frequency in the range of 1-200 Hz

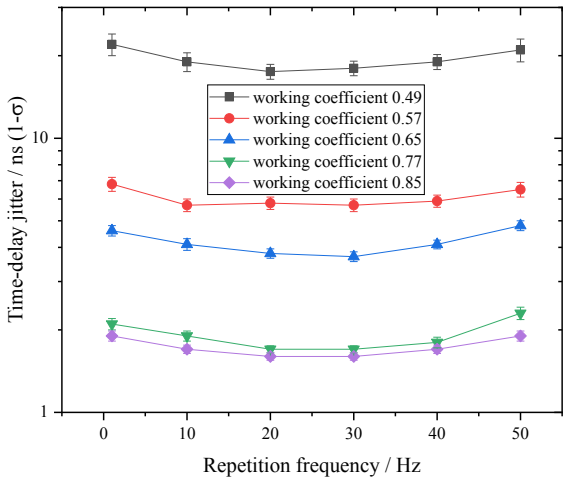


Fig. 5. Variation of time-delay jitter with repetition frequency in the range of 1-50 Hz.

Fig. 5 shows an enlarged view for the time-delay jitter variation with repetition frequency up to only 50 Hz. It is obvious that as the repetition frequency starts to increase, there is an initial decrease before the jitter starts to increase, with *the minimum values obtained in the range between 20 Hz and 30 Hz*. Therefore, the experimental results seem to confirm the correctness of the prediction provided in Fig. 1: *there is indeed an optimal repetition frequency range, for which the time-delay jitter reaches a minimum value*. This result can be explained since at higher repetition rates, the insulation properties of the gas are not fully recovered during the time interval between two consecutive pulses. For higher and higher repetition rates, the gas is more easily ionized and the presence of residual (seed) electrons makes a discharge channel easier to be produced and reduces the statistical time delay of the next breakdown. As a consequence, the time-delay jitter is also slightly lowered. However, as the operation frequency is further increased, the recovery time of the gas is reduced, resulting in a decrease in the insulation ability, which causes an increase in the instability of the gas discharge, thereby causing an increase in the time-delay jitter. It also can be seen that when the working coefficient exceeds 0.6, the time-delay jitter has better stability, and its dispersion is less than ±5%, as shown by the error bar in Fig. 5.

In order to study the above phenomena in more detail and obtain the optimal conditions for minimizing the time-delay jitter, the *individual* time-delay jitter of the two gaps was also studied. Fig. 6 presents the time-delay jitter for each gap separately as a function of the voltage working coefficient at a repetition rate of 30 Hz and for the three different trigger pulses mentioned above. It can be seen that when the voltage time rate-of-change of the trigger pulse is 0.25 kV/ns, the time-delay jitter of gap 1 is basically stabilized at about 1.8 ns, a fact that seems to have no relationship with the working coefficient. In contrast, the jitter of gap 2 is depending on the working coefficient: when the coefficient increases up to about 0.75, the jitter decreases rapidly from 17 ns down to 0.5 ns and for even larger working coefficients it stabilizes at a sub-nanosecond value. This result shows that when the working coefficient is lower than 0.65, the jitter of the switch is clearly dominated by the gap 2 jitter, while for working coefficients higher than 0.75 the gap 1 jitter is dominant as it accounts for more than 75% of the overall jitter of the switch.

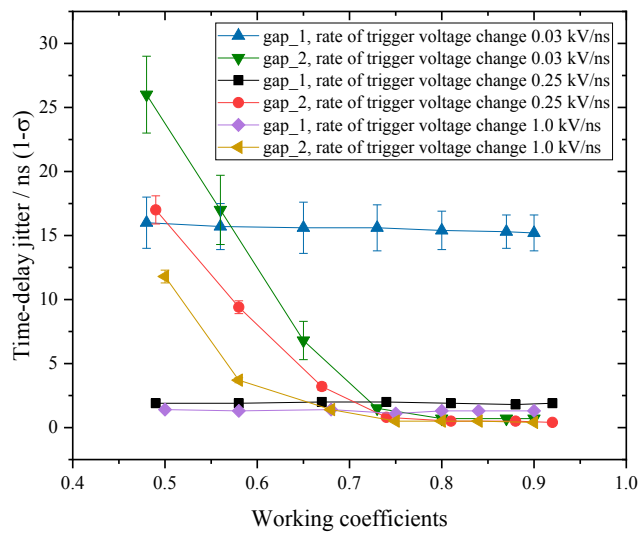


Fig. 6. Time-delay jitter of gap 1 and gap 2 as a function of the voltage working coefficient for a repetition rate of 30Hz and for the three different trigger pulses described in text.

Fig. 6 also demonstrates that the higher the voltage time rate-of-change dV/dt of the trigger pulse, the smaller the gap 1 jitter: for dV/dt having the values 0.03 kV/ns, 0.25 kV/ns, and 1.0 kV/ns, the jitter of gap 1 is correspondingly 15.6 ns, 1.7 ns, and 1.1 ns.

The explanation is that gap 1 is affected mainly by the electric field distortion caused by the trigger pulse and a trigger pulse with a faster rise time will more easily promote the generation of initial electrons and so reduce the statistical time delay and therefore the jitter.

In contrast, because gap 2 operates in a self-breaking mode, its time-delay jitter is affected mainly by the voltage working coefficient. The higher the applied voltage, the easier it is to generate the

initial electrons in the gap and the formation and development speed of the electron collapse are also faster, making the time delay much lower.

When the operation frequency is increased, both the time-delay jitter of gap 1 and of gap 2 tend to decrease first and then increase, which is consistent with the data of Fig.4 for the total time-delay jitter of the switch. When the switch operates at a low voltage working coefficient, as the operation frequency increases, the time-delay jitter of gap 2 dominates the total time-delay jitter of the switch. However, when the voltage time rate-of-change of the trigger pulse is too small, the time-delay jitter of the gap 1 may constitute the major proportion of the total time-delay jitter of the switch.

IV. CONCLUSION

In summary, using simple considerations for the gas breakdown phenomena, it was predicted that for an electrically triggered field-distortion spark gap there should be an optimal operation frequency range for which the time-delay jitter is lowest. It was also stated that the optimum operation frequency range should vary depending on the filling gas properties and spark gap distances. The experimental results confirm the correctness of these predictions. In particular, the results demonstrate that when the spark gap is filled with a gas mixture of 30% SF_6 and 70% N_2, the optimum repetition frequency that minimizes the time-delay jitter is in the range between 20 Hz and 30 Hz. The time-delay jitter can be further reduced over this optimal operation frequency range by operating at a high voltage working coefficient and using the trigger pulse with the highest voltage time rate-of-change.

REFERENCES

[1] 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.

[2] 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.

[3] J. D. Zhang, X. J. Ge, J. Zhang, J. T. He, Y. W. Fan, Z. Q. Li, Z. X. Jin, L. Gao, J. P. Ling and Z. M. Qi, "Research progresses on Cherenkov and transit-time high-power microwave sources at NUDT," Matter and Radiation at Extreme, 1, pp. 163-178, 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] 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.

[6] 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.

[7] S. J. MacGregor, S. M. Turnbull, F. A. Tuema and O. Farish, "Factors affecting and methods of Improving the pulse repetition frequency of pulsed-charged and DC-charged high-pressure gas switched," IEEE Trans. Plasma Sci., vol. 25, no. 2, pp. 110-117, Apr. 1997.

[8] A. Saxena, S. Tewari, N. M. Singh, A. Sharma and K. C. Mittal, "Simulation of breakdown mechanism in high power spark gaps filled with nitrogen gas at atmospheric pressure," Radiation Effects & Defects in Solids, vol. 170, no. 2, pp. 111-120, 2015.

[9] Y. J. Chen, J. J. Mankowski, J. C. Dickens, J. Walter and M. Kristiansen, "Low-jitter triggered spark gap with high-pressure gas mixtures," IEEE Trans. Plasma Sci., vol. 36, no. 5, pp.2546-2553, Oct. 2008.

[10] L. Arantchouk, A. Houard, Y. Brelet, J. Carbonnel, J. Larour, Y. -B. Andre and A. Mysyrowicz, "A simple high-voltage high current spark gap with subnanosecond jitter triggered by femtosecond laser filamentation," Appl. Phys. Letter., vol. 102, 163502, 2013.

[11] J. R. Woodworth, J. A. Alexander, W. A. Stygar, L. F. Bennett, H. D. Anderson, M. J. Harden, J. R. Blickem, F. R. Gruner and R. White, "Low inductance switching studies for Linear Transformer Drivers," in *IEEE Pulsed Power Conf.*, Washington, DC, USA, Jun. 2009, pp. 250-254.

[12] J. J. Leckbee, G. E. Pena, M. L. Kiefer, J. A. Alexander, B. S. Stoltzfus, J. L. Brown, H. Wigelsworth, F. E. White and B. Bui, "Comparison of trigger requirements for gas switched for Linear Transformer Drivers," in *IEEE Int. Power Modulator and High Voltage Conf.*, 2014, pp. 93-96.

[13] H. Tang and V. Scuka, "The breakdown mechanism of mid-plane triggered spark gap trigatron," IEEE Trans. Dielectr. Electr. Insul., vol. 3, no. 6, pp. 843-848, Dec. 1996.

[14] M. G. Grothaus, S. L. Moran and L. W. Hardesty, "Recovery characteristic of Hydrogen spark gap switches," Proceedings of the IEEE Pulsed Power Conference, Albuquerque, NM, USA, pp. 475-478, 1993.

[15] S. J. MacGregor, F. A. Tuema, S. M. Turnbull and O. Farish, "The operation of repetitive high-pressure spark gap switches," J. Phys. D Appl. Phys., vol. 26, pp. 954-958, 1993.

[16] Y. Yin, J. L. Liu, H. H. Zhong and J. H. Feng, "Experimental study of the voltage recovery characteristics of spark gap switch with different gases," IEEE 16th Intern. Pulsed Power and Plasma Sci. Conf., Albuquerque, NM, USA, pp. 459-463, 2007.

[17] Y. Chen, J. Mankowski, J. Walter, J. Dickens and M. Kristiansen, "Jitter and recovery rate of a trigger spark gap with high pressure gas mixtures," IEEE 16th Intern. Pulsed Power and Plasma Sci. Conf., Albuquerque, NM, USA, pp. 254-257, 2007.

[18] J. MacGregor, O. Farish and I. D. Chalmers, "The switching properties of SF_6 gas mixture," IEEE 7th Intern. Pulsed Power Conf., Monterey, CA, USA, pp. 510-513, 1989.

[19] Y. Chen, J. Dickens, J. Mankowski and M. Kristiansen, "Optimization of a low jitter, 50 kV, 100 Hz, triggered spark gap with high pressure gas mixtures," IEEE Trans. Dielectr. Electr. Insul., vol. 16, no. 4, pp. 971-977, August 2009.

[20] 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.

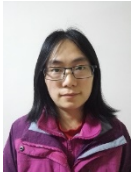
[21] J. R. Woodworth, J. A. Alexander, F. R. Gruner, W. A. Stygar, M. J. Harden, J. R. Blickem, G. J. Dension, F. E. White, L. M. Lucero, H. D. Anderson, L. F. Bennett, S. F. Glover, D. Van DeValde and M. G. Mazarakis, "Low-inductance gas switches for linear transformer drivers," Phys. Rev. ST Accel.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

[22] N. H. Malik and A. H. Qureshi, "A review of electrical breakdown in mixtures of SF_6 and other Gases", IEEE Trans. Electr. Insul., vol. EI-14, no. 1, pp. 1-13, Feb. 1979.

Falun Song was born in Shandong province, China, in 1977. He received the B.S. degree from Liaocheng Normal University, Liaocheng, China, in 2000 and the Ph.D. degree from University of Science and Technology of China, Anhui, China, in 2005. He is currently an Associate Professor with Institute of Applied Electronics, China Academy of Engineering Physics. He is working on pulsed power and plasma immersion ion implantation technology. He is currently an academic visitor in Loughborough University, Loughborough, Leicestershire, UK.

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

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



Chunxia Li was born in Sichuan province, China, in 1983. She graduated in 2005 from Tsinghua University, Beijing, China. Her research interests are pulsed power technology and electron beam diagnostic technology.

Ganping Wang was born in Shandong province, China, in 1983. He received the B.S. degree in 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 Graduate school of China Academy of Engineering Physics (CAEP), Beijing, China, in 2009. He is currently working toward the Ph.D. degree in physics of Wireless Electronics from Graduate school of CAEP. His research interests are high-power pulsed power technology.

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

Yanqing Gan was born in Gansu province, China, in 1970. He has been engaged in the research of pulsed power sources for more than twenty-seven years. He is working on pulsed power measurement technology and plasma diagnostic technology.

Xiao Jin was born in Zhejiang province, China, in 1969. He received the B.S. degree from Tsinghua University, Beijing, China, in 1992 and the Ph.D. degree from Graduate school of China Academy of Engineering Physics, Beijing, in 2002, and became a professor in 2006. His research interests are the 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 working toward the Ph. D. degree in China State Key Laboratory of Advanced Welding and Joining at 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.