

Photoconductive switching of an air-filled high-voltage spark gap : Pushing the limits of spark gap switching

Citation for published version (APA):

Hendriks, J., & Brussaard, G. J. H. (2006). Photoconductive switching of an air-filled high-voltage spark gap : Pushing the limits of spark gap switching. In *Proceedings of the 27th International Power Modulator Conference, 14-18 May 2006, Washington DC, USA* (pp. 431-434). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/MODSYM.2006.365276>

DOI:

[10.1109/MODSYM.2006.365276](https://doi.org/10.1109/MODSYM.2006.365276)

Document status and date:

Published: 01/01/2006

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Photoconductive Switching of an Air-Filled High-Voltage Spark Gap: Pushing the Limits of Spark Gap Switching

J. Hendriks and G.J.H. Brussaard

Eindhoven University of Technology, Department of Applied Physics
P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Abstract—In this contribution we present the recent results on photoconductive spark gap switching. This new way of switching combines the benefits of both laser-triggered spark gap switches and photoconductive semiconductor switches. High voltages can now be switched with rise times of the order ps and almost no time jitter. We will also show that for this new way of switching, conventional theory is no longer sufficient to describe the switching behavior. A new approach of theoretical spark gap optimization is required to push the limits further.

I. INTRODUCTION

Photoconductive switching of an atmospheric, air-filled spark gap by a high-power femtosecond laser is a novel approach for switching high voltages into pulses with a very fast rise time (order ps) and no shot-to-shot time variation (jitter) [1-3]. It combines the benefits of two fields of high-voltage switching: First, laser-triggered spark gap switching where the switching medium is either gas or liquid and a laser is used to initiate the breakdown of the gap. Second, photoconductive switching where the switching medium is a semiconductor device, which is completely illuminated by a short pulsed laser.

When the complete (gas-filled) gap is sufficiently ionized by a femtosecond, high-power laser, stochastic breakdown processes (dominant in the laser-triggered switch), no longer determine the actual breakdown-behavior of the gap. The time jitter will then only be determined by the jitter of the switching laser (as in the semiconductor switch). On the other hand, because the switching medium is a gas, high currents can be switched without permanently damaging the switch.

Photoconductive spark gap switching requires a new way of modeling. Plasma processes are no longer dominant for the switching behavior [4]; therefore, electrodynamic details of the switching process become dominant. These details cannot be modeled with conventional lumped element or transmission line models. We developed a three-dimensional electrodynamic model to simulate the switching behavior of the photoconductive spark gap, and to optimize its geometry to improve the output pulse [5, 6].

The photoconductively switched spark gap makes it possible to synchronize high-voltage pulses more accurately. Possible future applications of photoconductively switched ultrashort pulses can be the creation of broadband, high-intensity terahertz radiation for medical and security purposes [7]. Also, research in the field of bioelectrics can be extended because

higher voltages with faster rise times become available [8]. Our purpose is to use these ultrafast high-voltage pulses to develop a new type of electron accelerator and its diagnostics [9, 10].

This contribution gives an overview of the experiments and simulations done on the photoconductive spark gap switch. A more detailed description can be found in [1].

II. SETUP

Photoconductive switching of a gas-filled spark gap requires far greater laser intensity than photoconductive switching of semiconductors. Throughout the gap the laser intensity needs to be high enough to create a plasma over the complete distance between the electrodes. This plasma has to be sufficiently ionized to pass over stochastic breakdown processes. For a gas-filled gap the intensity has to be above the threshold for tunneling ionization, around 10^{18} Wm⁻² for most gases. Subsequently, this ionization has to occur on a time scale much smaller than the target for the rise time of the switched high-voltage pulse. A high-power femtosecond Ti:Sapphire laser meets both these requirements. Our Ti:Sapphire laser system produces 200 fs laser pulses with an energy of 35 mJ (~0.2 TW) at a repetition frequency of 10 Hz.

The spark gap, together with the switching laser, are depicted in Fig. 1. The inner conductor of the transmission line (diameter 6 mm) was made of copper, the outer conductor (diameter 15 mm) was made of brass (characteristic impedance 55 Ω). The tips of the inner conductors were made of copper-tungsten and can be replaced. The gap distance between the two inner conductors could be varied. It was set here to 1 mm. The gap can be filled either with atmospheric air or a flow of nitrogen-gas.

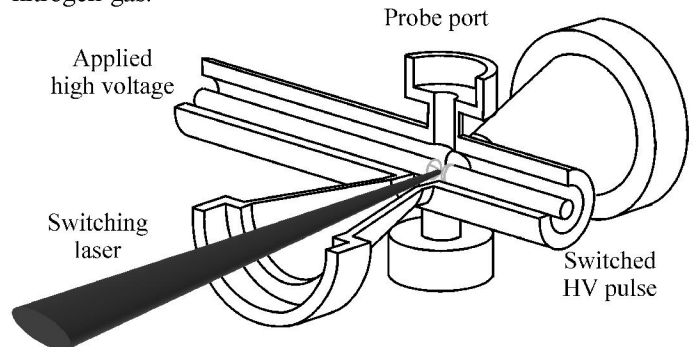


Fig. 1. Cut-view representation of the photoconductive spark gap together with the switching laser.

Horizontal ports for the switching laser and vertical ports for diagnostic purposes were present to enter the gap region.

While the setup was designed such that it was able to hold off 2 MV, 1 ns pulses, we applied for the first experiments voltages up to 5 kV. The switched pulses were measured capacitively by a 1.5 GHz, 8 GSa HP Infinium oscilloscope and integrated offline.

III. EXPERIMENTAL SWITCHING RESULTS

We first varied the laser energy and monitored the switched pulses. The gap, filled with atmospheric air, was charged to a voltage of 4.5 kV, which is about 90% of the self-breakdown voltage of the spark gap. Pulses switched with increasing laser energy are given in Fig. 2. When the laser energy is low (bottom curve), no gap-filling path is ionized between the conductors. The spark gap is triggered, not switched, and stochastic avalanche and streamer processes cause the breakdown of the gap. The time jitter (σ) at this low laser energy is of the order ns, as indicated in the figure. When the laser energy is increased, enough laser power is available to create a gap-filling plasma. A small step in the output pulse becomes visible just after the laser pulse has arrived. However, the initial resistance of the laser created plasma is relatively high, and therefore only a small part of the voltage is switched in this first step. Stochastic breakdown processes are passed over here and the jitter is reduced enormously. Increasing the laser energy further results in a higher first step of the switched pulse due to the decreasing resistance of the laser created plasma. Finally, enough laser energy is available to switch the complete voltage in the first rising edge of the pulse. Now, the pulse has a squared shape and its width (2 ns) is determined by the length of the charged transmission line only. The rise time is 100 ps and the time jitter is 15 ps, both limited by the resolution of our measurement equipment. The small pulse directly behind the main pulse is likely to be caused by reflections on the transmission line-plasma boundary.

When the height of the first rising edge of the switched pulses is plotted as a function of laser energy (see Fig. 3.), two regimes become visible. First, the regime where the applied

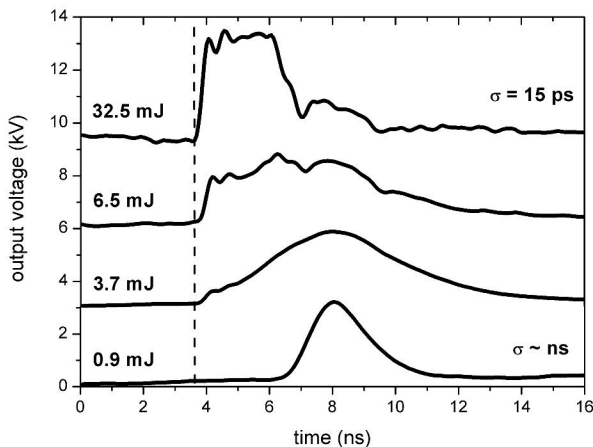


Fig. 2. Switched pulses with increasing laser energy ($V_{\text{gap}} = 4.5$ kV, atm. air, gap = 1 mm). The curves are vertically offset for clarity. The arrival time of the laser is indicated by the dashed line, the time jitter is given as σ .

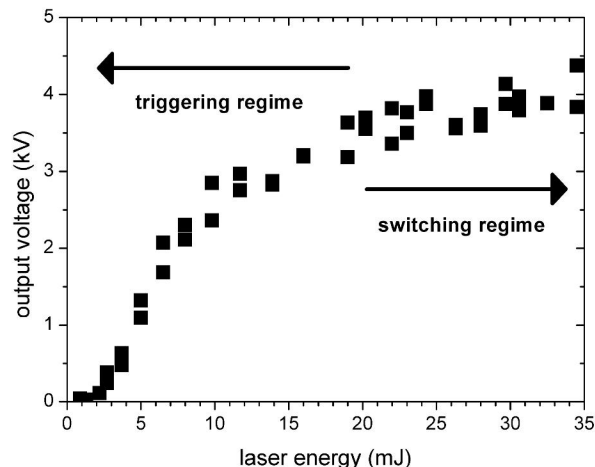


Fig. 3. Amplitude of the first rising edge of the switched pulses, as depicted in Fig. 2. Each point is a separate measurement.

voltage (4.5 kV here) is not switched completely in the first rising edge of the pulse. The resistance of the laser-created plasma drops with increasing laser energy and the amount of voltage that is switched in the first rising edge increases. We called this the "triggering regime" in Fig. 3. Secondly, the regime where an increase in laser energy has no significant influence anymore on the height of the first rising edge and the shape of the pulse. The full applied voltage is switched immediately. We called this saturated regime the "photoconductive switching regime".

In order to investigate the voltage range that can be switched photoconductively with the same spark gap setup, we varied the applied voltage (see Fig. 4.). We made sure that the laser energy was high enough to be in the photoconductive regime of Fig. 3 (34 mJ here). The gap distance was kept constant at 1 mm and the gap was filled with atmospheric air. The highest applied voltage (5.1 kV) was just below the self-breakdown voltage of the gap. Here the pulse shape is similar to the 32.5 mJ pulse of Fig. 2, a rectangular pulse with a sharp rising edge. At lower applied voltages, this shape is sustained. It was possible to switch voltages as low as 10% of the self-

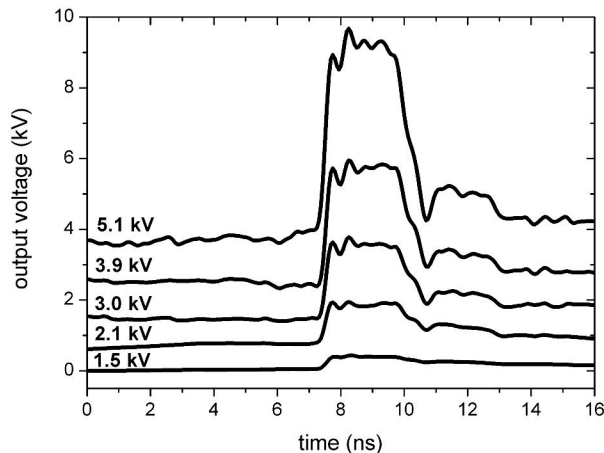


Fig. 4. Pulses switched with different applied voltages and constant laser energy (34 mJ, gap = 1 mm, atm. air). The curves are vertically offset for clarity.

breakdown voltage (lower than 10% could not be measured with the present measurement setup). It has to be mentioned that at lower applied voltages (80% of the self-breakdown voltage and lower), a part of the voltage is lost over the gap. The current that runs through the plasma during switching is then insufficiently high to keep the resistance of the plasma low [4]. Although no longer 100% efficient, switching is still possible. Compared to the laser-triggered spark gap operating range (between 80% and 100% of the self-breakdown voltage), this is a major improvement that extends the applicability of gas-filled switches enormously.

The measurements described here were also done with a flow of nitrogen through the gap region (over-pressure typically 0.2 bar). The results do not differ significantly from the results obtained when switching in air.

IV. ELECTRODYNAMIC MODELING AND OPTIMIZATION

We had two reasons to model the photoconductive spark gap switch and to get more insight into the switching details. First, in laser-triggered spark gaps, the rise time is comparable to, and thus limited by, the plasma formation time. Electrodynamics details of the switching process are negligible on this time scale. However, at photoconductive switching, these electromagnetic details of the switching process are dominant, since the plasma is created almost instantaneously. Lumped element and transmission line models are often used for modeling laser-triggered spark gaps. Unfortunately, these models are not able to describe these electrodynamic effects in detail and can not therefore, be used to model the photoconductive spark gap switch. Another reason for modeling is that we were not able to resolve the rise time of the photoconductively switched pulses because of the limited measurement resolution of the measurement equipment.

We developed a three-dimensional electromagnetic model that simulates the electromagnetic field-propagation in the photoconductively switched spark gap and predicts the rise time for different spark gap geometries. The model is implemented in CST Microwave Studio [11], which is a commercially available electromagnetic solver. Details of this model can be found in [5]. A benefit of this model is that discontinuities in the geometry, like the ports for the laser, can be taken into account. This was not possible with the lumped element and transmission line models.

In order to get an idea of the rise time of the photoconductively switched pulses in our spark gap (Fig. 1.), we modeled this gap, with and without, laser and probe ports. The pulse shape of the simulated switched pulse (without ports) is given in Fig. 5. It has a nice rising edge with a rise time of 19 ps. Investigation of the electromagnetic field propagation reveals that this rise time is determined by the time it takes for a stable TEM-mode to build up in the gap region (not treated here, see [5]). When the laser creates the plasma and, subsequently, the current starts to run through it, an electromagnetic field-disturbance starts to propagate spherically outward from the plasma. When it reaches the outer conductor, only the TEM-mode can propagate further, without

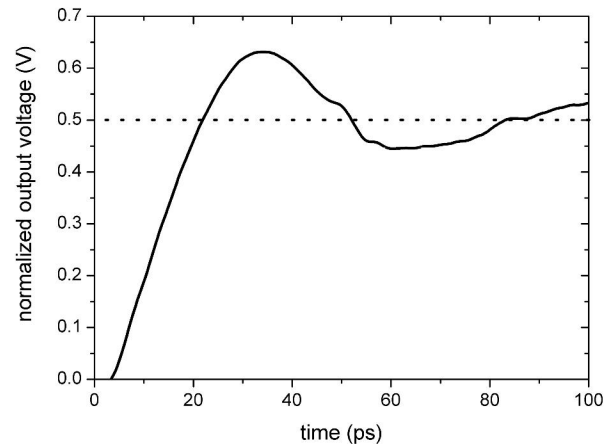


Fig. 5. Simulated output signal after photoconductive switching. The dotted line indicates the final value.

dispersion, towards the output. Therefore, the rise time depends on the geometry of the gap region. Also, some overshoot is visible, together with oscillations on top of the pulse. The overshoot and oscillations are unwanted features. This, together with the interest in the limits of the achievable rise time, requires spark gap optimization.

In the literature, optimization of spark gap structures is based on lumped element and transmission line theory. Minimization of the gap inductance minimizes the rise time, according to lumped element theory. Transmission line theory requires the impedance throughout the whole spark gap to be as constant as possible. This way, power loss due to reflections is minimized. The suggested optimal spark gap geometry is based on both these arguments. It is a biconical gap with a minimal gap inductance and a quasi-constant impedance throughout the structure (Fig. 6., [12, 13]).

However, if we simulate this biconical geometry with our electrodynamic model, the result is far from optimal (see Fig. 7). The steep rising edge turns halfway to its final value into a slowly oscillating signal. It takes, compared to the signal of Fig. 5., a long time before the final value is reached. The gap behaves like an over-damped system. This means that the suggested optimal geometry for laser-triggered spark gaps is not optimal for photoconductive spark gap switching.

Fig. 5. shows an under-damped system, Fig. 7. an over-damped one. For an optimal output, the system should be a critically damped system, preferably without oscillations on top of the switched pulse. The amount of damping is caused by the way the electromagnetic fields, which propagate spherically

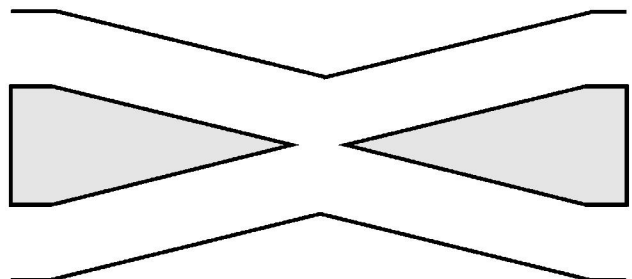


Fig. 6. In the literature suggested optimal spark gap configuration.

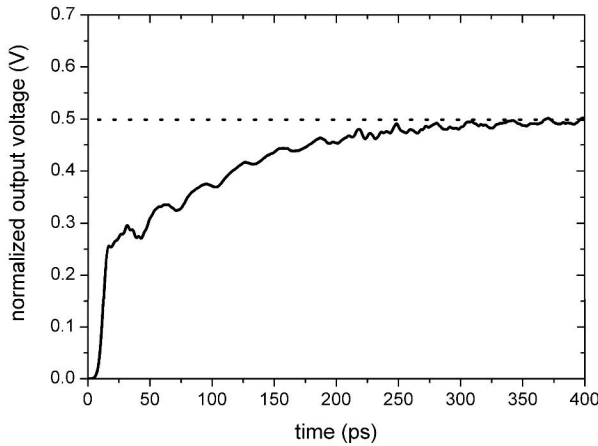


Fig. 7. Simulated output signal of the biconical spark gap. The dotted line indicates the final value.

from the plasma to the outer conductor, reflect on the outer conductor and interfere with the initial field again. The amount of reflection and interference of the electromagnetic fields can be influenced by changing the sharpness of the inner conductor and adjusting the constriction of the outer conductor (a visualization can be found in [6]). This way, the optimal spark gap geometry for photoconductive spark gap switching can be found that produces nice square pulses without significant oscillations. This is depicted in Fig. 8. The geometry of the spark gap region is still the determining factor for the rise time.

IV. CONCLUSIONS

With our spark gap setup, we proved the principle of photoconductive high-voltage switching in air and nitrogen by using a high-power femtosecond laser. We showed a clear transition from laser-triggered switching to photoconductive switching when the laser power is increased. The time jitter dropped dramatically when going from the laser-triggered regime to the photoconductive switching regime. Stochastic breakdown processes that dominate the switching behavior in the triggering regime are passed over at photoconductive

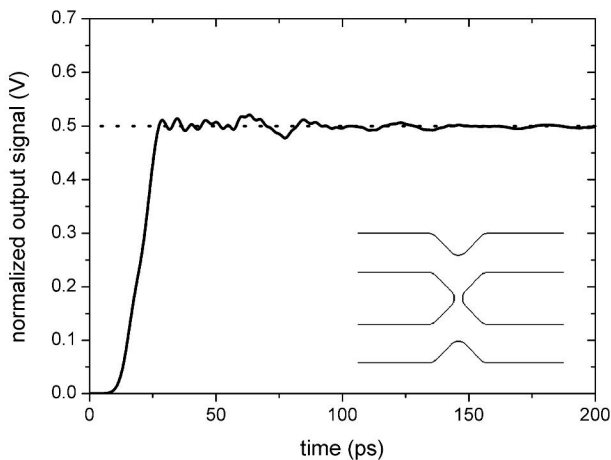


Fig. 8. Simulated output signal of the optimal spark gap configuration for photoconductive switching. The gap configuration is also depicted. Remember that the gap distance is 1 mm.

switching. Photoconductive switching makes it possible to use the same spark gap to switch voltages as low as 10% of the self-breakdown voltage.

Conventional lumped element and transmission line theories, used for modeling and optimizing laser-triggered spark gaps, are no longer accurate for modeling the photoconductive spark gap switch. Due to the extremely short time scales at photoconductive switching, electrodynamic details of the switching process become dominant. Therefore, we developed a model to simulate the electrodynamic field propagation in three dimensions and to determine the rise time of a photoconductively switched pulse. Also, a new optimization procedure is developed to optimize the spark gap configuration to get a nice square shaped output pulse.

ACKNOWLEDGMENT

This research was funded by the Technology Foundation STW, applied science division of NWO and the technology program of the Ministry of Economic Affairs and the Royal Netherlands Academy of Arts and Sciences (KNAW).

REFERENCES

- [1] J. Hendriks, "The physics of photoconductive spark gap switching: Pushing the frontiers", Ph.D. Thesis, Eindhoven University of Technology, 2006.
- [2] G.J.H. Brussaard and J. Hendriks, "Photoconductive switching of a high voltage spark gap", *Appl. Phys. Lett.*, 86, 081503, 2005.
- [3] J. Hendriks, B.H.P. Broks, J.J.A.M. van der Mullen and G.J.H. Brussaard, "Experimental investigation of an atmospheric photoconductively switched high voltage spark gap", *J. Appl. Phys.*, 98, 043309, 2005.
- [4] B.H.P. Broks, J. Hendriks, W.J.M. Brok, G.J.H. Brussaard and J.J.A.M. van der Mullen, "Theoretical investigation of a photoconductively switched high voltage spark gap", *J. Appl. Phys.*, in press.
- [5] J. Hendriks, S.B. van der Geer and G.J.H. Brussaard, "Electrodynamic simulations of a photoconductively switched high voltage spark gap", *J. Phys. D: Appl. Phys.*, 38, 2798, 2005.
- [6] J. Hendriks, S.B. van der Geer and G.J.H. Brussaard, "Spark gap optimization by electrodynamic simulations", *J. Phys. D: Appl. Phys.*, 39, 274, 2006.
- [7] News feature, *Nature* 424, pp. 721, 2003.
- [8] K.H. Schoenbach, S. Katsuki, R.H. Stark, E.S. Buescher and S.J. Beebe, *IEEE Trans. Plasma Sci.*, 30 (1) pp. 293, 2002.
- [9] S.B. van der Geer, M.J. de Loos, G.J.H. Brussaard, O.J. Luiten and M.J. van der Wiel, "A 1 GV/m laser-triggered compact accelerator", *Proc. Eur. Particle Accelerator Conf.*, Paris, France, June 3-7 2002, pp. 989.
- [10] M.J. de Loos, S.B. van der Geer, F.B. Kiewiet, O.J. Luiten and M.J. van der Wiel, "A high-brightness pre-accelerated RF-photo injector", *Proc. Eur. Particle Accelerator Conf.*, Paris, France, June 3-7 2002, pp. 1831.
- [11] 2003 CST Microwave Studio Version 5, CST GmbH, Germany.
- [12] J.M. Lehr, C.E. Baum, W.D. Prather and R.J. Torres, *Ultra-Wideband, Short Pulse Electromagnetics*, vol. 4, pp. 11, ed. E. Heyman, New York: Plenum, 1999.
- [13] J.W. Spears, H. Krompholz and L.L. Hatfield, "sub-ns point-plane gas breakdown in a conical-shaped spark gap", *Proc. 14th IEEE Int. Pulsed Power Conf.*, Dallas, TX, 2003, pp. 1347.