Picosecond High Voltage Switching of a Pressurized Spark Gap

Document status and date:
Published: 01/01/2003

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

PICOSECOND HIGH VOLTAGE SWITCHING OF A PRESSURIZED SPARK GAP

J. Hendriks[*] and G.J.H. Brussaard

Eindhoven University of Technology, Department of Applied Physics, Center for Plasma Physics and Radiation Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

Abstract

Laser wakefield acceleration promises the production of high energy electrons from table-top accelerators. External injection of (low energy) electrons into a laser wakefield puts extreme demands on the shortness and timing, i.e. a fraction of a plasma period, typically less than 100 fs. In order to meet these requirements, we have revisited the concept of pulsed DC acceleration. Simulations have shown that this concept can be successful if high voltage pulses (of the order MV) can be switched with picosecond precision. As a first step towards this goal, a 10 kV laser triggered pressurized spark gap was designed and built.

One of the limitations on risetime and jitter in high voltage laser triggered spark gaps is the initial breakdown process. Since this is a stochastic process it will cause jitter, and the growth rate of the plasma will determine the fastest possible risetime of the pulse. A way to overcome this limitation is to create a line focus between the electrodes, using a high power femtosecond laser. At laser intensities above approximately 10^{18} W/m^2 near-threshold or tunneling ionization causes near-instantaneous ionization of a complete plasma channel between the electrodes, much like a photoconductive semi-conductor switch. Because of the instantaneous ionization and the high degree of ionization in the plasma channel, jitter and risetime are reduced considerably.

We will present the first results from switching of a 10 kV spark gap with 3 mm inter-electrode distance, using a femtosecond Ti:Sapphire laser. A line focus of the laser is created, using cylindrical optics. Folded-wave interferometry will be described to study the development of the plasma channel on femtosecond timescales.

I. INTRODUCTION

When accelerating very short high-brightness electron bunches, internal Coulomb forces will rapidly reduce the (phase-space) density. This space-charge explosion can be limited if the electrons are accelerated to relativistic (10 MeV) energies over a very short distance. Vacuum breakdown limits the field inside state-of-the-art RF injectors to approximately 100 MV/m. It is possible to create higher gradients if very short high-voltage pulses

are applied in a diode configuration [1]. The target is to produce 10 MeV bunches and in order to keep the accelerator compact, a *modest* 2 MV pulser will be used [2]. This requires stacking of multiple accelerating stages that are switched in rapid succession. A 2 MV pulse generates a 1 GV/m field in a diode of 2 mm. In order to maintain a high average accelerating field, the distance between the acceleration stages should not be more than a few mm, requiring switching times of only a few picoseconds.

In a common high-voltage laser-triggered spark-gap, risetime and jitter are limited by the initial breakdown process [3]. A (much simplified) picture of this process of breakdown is drawn in Figure 1. In Fig. 1(a), the situation of spontaneous breakdown in a spark gap is shown. After applying the high voltage, electrons generated by field emission will start heating the electrodes, until enough electrons are produced to cause the breakdown. There is a long delay between applying the high voltage on the gap and the actual breakdown, caused by the stochastic nature of the breakdown process. This stochastic behavior also causes large jitter of the high voltage pulse. Focusing a laser in the gap will create a plasma which speeds up the breakdown process (Fig. 1(b)). The delay is less than at spontaneous breakdown and also the jitter is reduced because the first free electrons are made at a well defined moment in time. If the laser power is increased further, it can ionize a plasma channel through which a current can run. Generally, the ionization from the current in the plasma channel is less than the quenching of the plasma by the insulating gas in the gap and the plasma is extinguished. The electrodes have been heated significantly, however, and breakdown will follow rapidly, and with much less jitter (Fig. 1(c)). A small pre-pulse from the current through the initial plasma channel can be observed. At even higher laser power, a plasma may be generated that will conduct a current which will sustain the plasma channel and breakdown will follow immediately (Fig. 1(d)). Jitter for the start of the pulse is reduced to the laser pulse duration. The risetime of the pulse will be determined by the degree in which the (initial) plasma channel is matched to the rest of the high-voltage system.

For a high degree of ionization of the insulating gas in the spark gap the laser intensity has to be above the threshold for tunneling ionization, typically 10^{18} W/m^2. In a gap with 3 mm inter-electrode distance (enough to hold

---

off the 2 MV, 1 ns pulse), a 1 TW femtosecond laser can create a plasma channel with a diameter of approximately 0.2 mm.
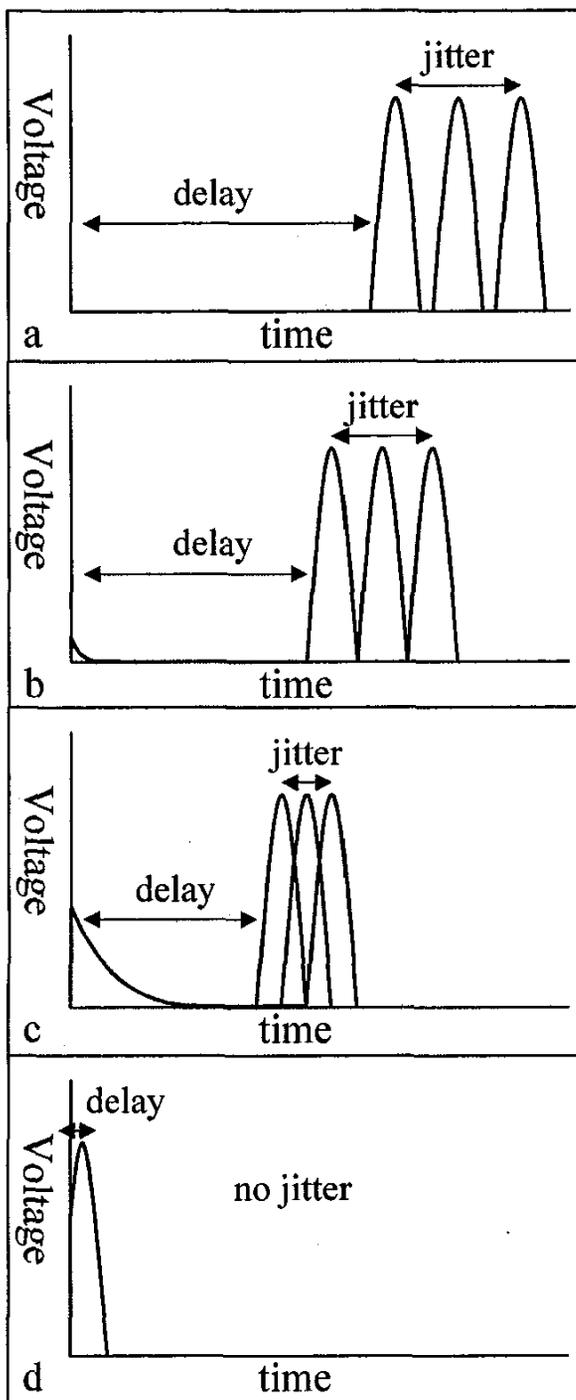

Figure 1. Graphical description of the breakdown process of differently triggered spark gaps. (a) spontaneous breakdown, (b) laser point focus, (c) line focus, (d) high intensity line focus.
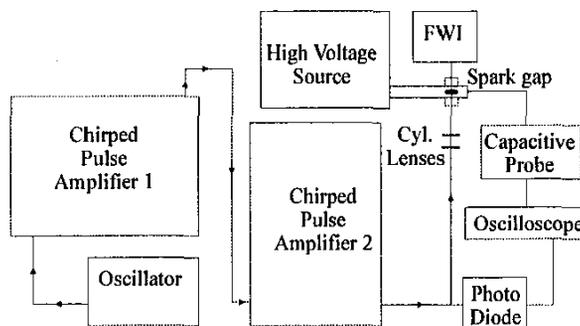

Figure 2. Overview of the setup. FWI is Folded Wave Interferometer.

II. EXPERIMENTAL SETUP

An overview of the experimental setup is given in Figure 2.

A. Femtosecond Ti:Sapphire Laser System and Optics

A 75 MHz mode-locked Ti:Sapphire laser oscillator (Femtolasers GmbH) produces laser pulses of 5 nJ and 15 fs @ 800 nm at 75 MHz repetition frequency. These pulses are amplified in a chirped pulse amplifier (CPA). A Ti:Sapphire crystal is pumped by a Nd:YLF laser (B.M. industries) at a repetition rate of 1 kHz with an energy of about 8 mJ @ 527 nm. This nine-pass amplifier produces pulses of 1 mJ, 25 fs (40 GW) at 1 kHz. The second CPA is still under construction. It is designed to produce 50 mJ, 50 fs (1 TW) pulses with a 10 Hz repetition frequency. In the experiments described here, the 40 GW pulses are used for switching the spark gap.

In order to create a cylindrical focus two cylindrical lenses are used. One lens ($f = 200$ mm) focuses in the horizontal plane, the other ($f = 150$ mm) in the vertical plane. Because the lenses can be moved separately, the size and shape of the resulting focus can be changed.

B. 30 KV Spark Gap

The high voltage spark gap setup consists of a 30 kV power supply (Lambda EMI 500A). This 30 kV power supply is connected to a ceramic high voltage resistor of 15 MΩ which is mounted to a transmission line of 30 cm length. The inner conductor ($\varnothing$ 6 mm) is made of Cu, the outer conductor ($\varnothing$ 15 mm) of brass. The transmission line is interrupted by a 3 mm spark gap. The self breakdown DC-voltage of this gap is approximately 10 kV in air (the experiments described here are done at DC instead of the pulsed 2 MV). The distance between the conductors is variable and the spark gap can be pressurized up to 2 bar. The tips of the spark gap conductors are made of CuW and can be changed. The end of the spark gap merges into a N-type cable connector.

588

C. Pulse Diagnostics

The high-voltage pulse is measured by a capacitive probe and recorded by a 1.5 GHz oscilloscope (HP Infinium). The laser pulse is measured by a photo diode. This signal is also used to trigger the oscilloscope. A CCD camera is installed on top of the spark gap setup. This camera is used to accurately position the focus of the laser between the electrodes and record emission from the spark.

III. FIRST RESULTS

Since the TW laser is still under construction, the first measurements are done using 1 mJ, 25 fs laser pulses (40 GW). The spark gap is reduced to 1.5 mm limiting the DC voltage on the transmission line to 4 kV.

The first measurements are comparable to the point focus situation as described in Fig. 1(b). 20 GW of laser power was focused in the spark gap. In Figure 3, a measured oscilloscope image is depicted. The laser pulse is measured on the photo diode, the HV pulse is measured capacitively. The HV pulse has a delay of about 33 ns and a jitter of 27 ns.
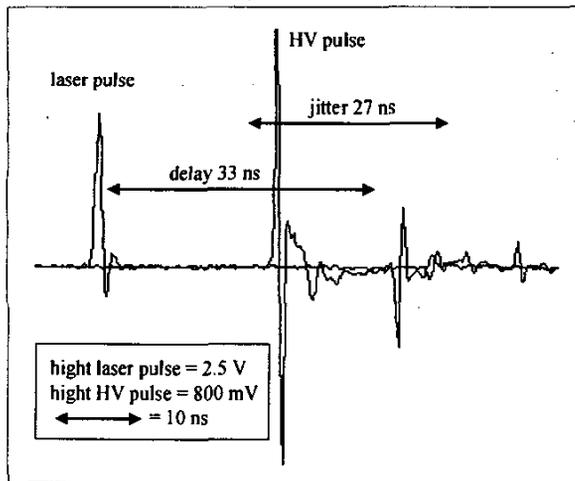

Figure 3. Oscilloscope image of measurement with 20 GW laser power. The HV pulse is measured capacitively. 4 kV is switched in a 1.5 mm gap.
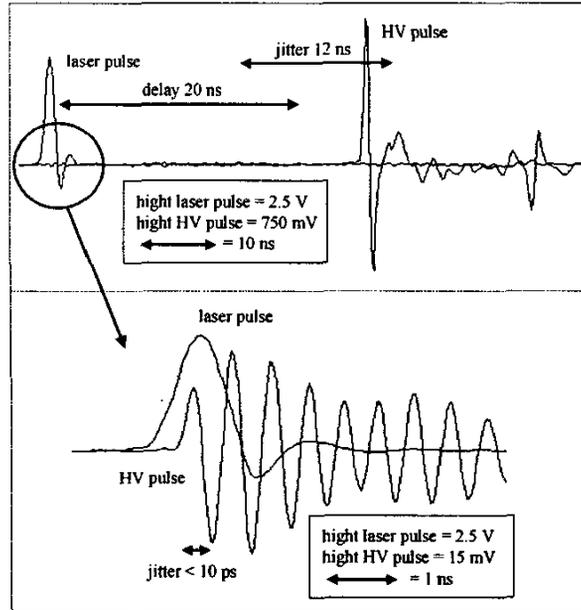

Figure 4. Oscilloscope image of measurement with 40 GW laser power. The HV pulse is measured capacitively. An enlargement of the pre-pulse is also given.

Next 40 GW laser power was used to create a plasma in the line focus of the cylindrical lenses. This is the same situation as described in Fig. 1(c). The oscilloscope image is given in Figure 4. At 40 GW laser power the delay between the laser pulse and the HV pulse has reduced to 20 ns and the jitter is now 12 ns. If the signal is investigated more closely, a pre-pulse is visible which is shown at the bottom of Fig. 4. This pre-pulse, followed by some reflections, is caused by the laser induced plasma and the jitter of this pre-pulse is less than 10 ps (the inherent jitter of the oscilloscope). The pre-pulse was not visible at the 20 GW measurements.

The effects observed in these experiments match the simple theory described before. By increasing the laser power, the delay between the laser pulse and the HV pulse is reduced, the jitter of the HV pulse is also reduced and a pre-pulse appears. The jitter of the pre-pulse is less than 10 ps. It is expected that if the laser power is increased further until the power is high enough to instantaneously ionize the complete spark gap, the pre-pulse can be used to switch with less than 10 ps jitter.

IV. OUTLOOK

The switching experiments will continue at higher power as the TW laser system approaches completion. Next, experiments will be conducted using a 2 MV, 1 ns pulse.

To study the switching process (plasma evolution and pulse formation) on a sub-picosecond timescale, folded-

wave interferometry and electo-optical measurement of the transmitted pulse are being setup.

A. *Interferometer*

Folded Wave Interferometry will be used to study the evolution of the created plasma on a fs timescale (Fig. 5). A part of the laser beam is used to probe the plasma. Because the probe beam is larger than the plasma, the beam can be folded after probing the plasma and an interference pattern will be visible on a ccd camera. Analyzing the phase differences gives a radial and an axial profile of the electron density as a function of position. By using a delay for the probing beam the spark can be probed at different times to get an insight in the evolution of the switching plasma.
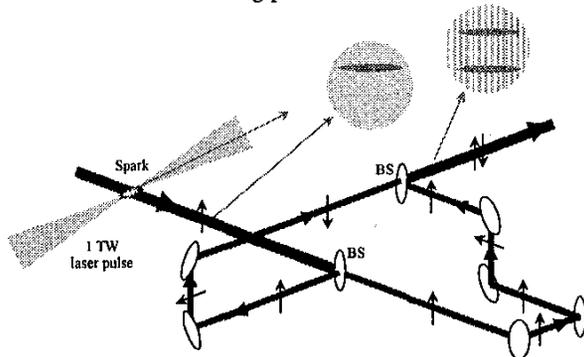

Figure 5. Scheme of the folded wave interferometer. The arrows indicate the position (up or down) of the spark in the beam. (BS = beam splitter)

B. *Electro-Optic Measurement*

The required ps-resolution cannot be measured by the oscilloscope that is used in the first experiments. This can be overcome by an electro-optical measurement. In such an experiment, a ZnTe crystal will be embedded in the setup after the spark gap. The electric field of the passing pulse induces birefringence by the Pockels effect. By probing the crystal with the fs Ti:Sapphire laser and scanning the delay of the probing pulse, the switched high voltage pulse can be measured on a sub-picosecond time scale [4,5].

V. SUMMARY

For the creation of compact, ultra-high brightness electron bunches, we developed a new accelerator concept based on GV/m acceleration gradients that goes beyond RF technology. This new concept requires high voltage switching of 2 MV, 1 ns pulses in a 3 mm spark gap with ps risetime and ps jitter. This ultrafast switching can be realized by using a TW, fs CPA lasersystem to instantaneously fully ionize the spark gap.

VI.   REFERENCES

[1] T. Srinivasan-Rao and J. Smedley, "Table top, relativistic, electron gun with GV/m gradient", 7th Advanced Accelerator Concepts Workshop, Lake Tahoe, CA, 1996.

[2] D. Vyuga and G.J.H. Brussaard, "A 2.5 MV subnanosecond pulser with laser triggered spark gap for the generation of high brightness electron bunches", these proceedings.

[3] J.M. Lehr, C.E. Baum, W.D. Prather and R.J. Torres, "Fundamental physical considerations for ultrafast spark gap switching" in ultra-wideband, short-pulse electromagnetics 4, e. Heyman, Ed. New York: Kluwer Academic/Plenum Publishers, 1999, pp. 11-20.

[4] X. Yan, A.M. MacLeod, W.A. Gillespie, G.M.H. Knippels, D. Oepts, A.F.G. van der Meer and W. Seidel, "Subpicosecond Electro-optic Measurement of Relativistic Electron Pulses", Phys. Rev. Lett. 85, 3404-3407 (2000).

[5] I. Wilke, A.M. Macleod, W.A. Gillespie, G. Berden, G.M.H. Knippels and A.F.G. van der Meer, "Single-Shot Electron-Beam Bunch Length Measurements", Phys. Rev. Lett. 88, 124801_1-124801_4 (2002).