PICOSECOND HIGH VOLTAGE SWITCHING FOR PULSED DC ACCELERATION

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Abstract

Laser wakefield acceleration promises the production of high energy electrons from table-top accelerators. External injection of a (low energy) electron bunch into a laser wakefield requires acceleration gradients of the order GV/m. In principle DC acceleration can achieve GV/m acceleration gradients. If high voltage pulses of the order MV can be switched with picosecond precision, the performance of such an accelerator would be greatly enhanced and even multistage DC acceleration would become feasible.

Presently risetime and jitter of high voltage pulses in high voltage laser triggered spark gaps are limited to the nanosecond regime by the initial stochastic breakdown process in the gap. A way to overcome this limitation is to create a line focus between the electrodes with an intensity above 10^{18} W/m^2 using a high power femtosecond Ti:Sapphire laser. Because of the instantaneous ionization and high degree of ionization in the plasma channel, picosecond switching precision can be achieved and jitter is reduced significantly.

A spark gap test setup with 3 mm interelectrode distance has been build and the first measurements have been done. Femtosecond diagnostics for characterization of the laser induced plasma and electro-optic diagnostics for the high voltage pulse have been developed.

INTRODUCTION

The creation of very short high-brightness relativistic electron bunches is limited by internal Coulomb forces. Phase-space density is rapidly reduced in the initial acceleration process due to the space-charge explosion. This space-charge explosion can be limited if the distance over which the electrons are accelerated to relativistic energies (10 MeV) can be made shorter. State-of-the-art RF injectors are limited to acceleration gradients of approximately 100 MV/m due to vacuum breakdown. Higher gradients can be achieved by applying very short high voltage pulses in a diode configuration [1]. The target is to produce 10 MeV high-brightness bunches in a compact accelerator. A "table top" 2 MV pulser is operational [2] and can create acceleration gradients of 1 GV/m in a diode of 2 mm. In order to accelerate up to 10 MeV, stacking of multiple, rapidly switchable acceleration stages is required. In order to keep the average acceleration field high, the distance between the stacked acceleration stages should not be more than a few mm. High voltage switching within only a few picoseconds is then required [3].

Next to the creation of high acceleration gradients, high voltage pulses with ps risetimes can also be used for the production of broadband high intensity Terahertz (THz) radiation. By coupling picosecond high voltage pulses into an antenna, THz radiation with intensities of the order of a magnitude higher than the common laser-semiconductor approach can be produced. This makes THz radiation even more suitable for imaging purposes in areas such as security and medicine [4].

Another promising field is bioelectrics, which investigates the possibility to control functions and membrane transport processes in biological cells by external pulsed electric fields. Biomedical material is exposed to short-pulsed, high field strengths that are now limited to the nanosecond time-regime due to nanosecond high voltage pulses. Exploration of higher field strengths and shorter pulses is of growing interest in this field [5].

THEORY

In conventional high voltage laser triggered spark gaps, risetime and jitter are limited by the initial breakdown process [6]. The stochastic behaviour of the electron avalanche causes jitter. The risetime of the high-voltage pulse is limited by the growth rate of the created plasma inside the gap (inductance). Increasing of the laser-power results in better control of the avalanche and thus jitter-reduction. If the laser-power is high enough, a line focus can be made inside the spark gap and the gap is ionized instantaneously. Laser triggering of the gap has now become (photoconductive) laser switching. Breakdown of the gap will follow immediately and jitter is reduced to the laser pulse duration. The risetime of the pulse will be determined by the matching of the plasma channel to the rest of the high voltage system [7].

A coaxial spark gap filled with atmospheric dry air and 3 mm inter-electrode distance is suitable to hold off 2 MV, 1 ns pulses. In order to get a high degree of ionization in the spark gap the laser intensity has to be above the threshold for tunnelling ionization (10^{18} W/m^2). A 1 TW, femtosecond laser is suitable for creation of a plasma channel in a 3 mm gap of about 0.2 mm diameter.

EXPERIMENTAL SETUP

The experimental setup consists of a Ti:Sapphire laser system, cylindrical lenses to create a line-shaped focus, a high voltage source connected to a spark gap and diagnostics to analyse the plasma and the high voltage pulse (figure 1).

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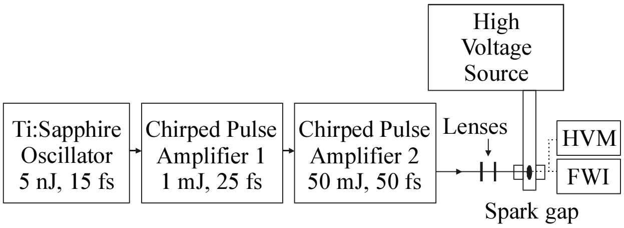

figure 1: Setup overview. HVM = electro-optic high voltage pulse measurement setup, FWI = folded wave interferometer for spark analyses.

Spark gap

As mentioned we use a coaxial spark gap (figure 2). The inner conductor is made of Cu and has a diameter of 6 mm. The outer conductor is made of brass and is 15 mm in diameter. The gap between the two inner conductors is 3 mm and can be varied. The tips of the two inner conductors are made of CuW and can be changed. The spark gap can be pressurized up to 2 bar. The first measurements are done at a 10 kV DC voltage and are descibed in [7].

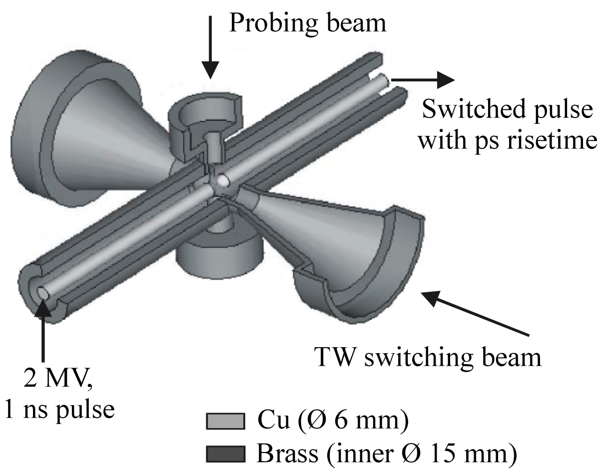

figure 2: Schematic representation of the coaxial spark gap. The vertical ports are for probing purposes. Through the horizontal cone-shaped port the TW laser pulse will enter the spark gap.

Femtosecond Ti:Sapphire laser system

The Ti:Sapphire laser system consists of three parts as depicted in figure 1. The mode-locked Ti:Sapphire laser oscillator (Femtolasers GmbH) produces laser pulses of 5 nJ, 15 fs @ 800 nm at a 75 MHz repetition rate. These pulses are amplified in the first chirped pulse amplifier (CPA). Here a Ti:Sapphire crystal is pumped by a Nd:YLF laser (B.M. industries) with an energy of 8 mJ @ 527 nm and a repetition rate of 1 kHz. After nine passes this first CPA has produced pulses of 1 mJ, 25 fs (40 GW) and the repetition rate can be 10 Hz or 1 kHz. Part of the red light is coupled out for other purposes and the remaining light is led into the second CPA. Here another Ti:Sapphire crystal is pumped by a Nd:YAG laser (Thales SAGA 230/10) with a pulse-energy of 1.25 J @ 532 nm at 10 Hz. After five amplification passes it produces 15 mJ. Upgrading up to 50 mJ is planned.

DIAGNOSTICS

In order to study the spark evolution and the high voltage pulse propagation in the spark gap in detail, two diagnostics are being developed. For plasma analysis a folded wave interferometer is installed and for the high voltage pulse characterization, an electro-optical setup is built. Electro-optical pulse characterization is chosen because ps-risetimes cannot be measured electronically.

Folded Wave Interferometer

The folded wave interferometer (FWI) is depicted in figure 3. With the FWI the evolution of the laser created plasma can be studied on a femtosecond timescale. Part of the high power laser beam will be used to probe the plasma. The probe beam is larger than the plasma and after it has probed the plasma, it can be folded and an interference pattern will be visible on a CCD camera. The switching plasma is visible by the phase changes in the interference pattern.

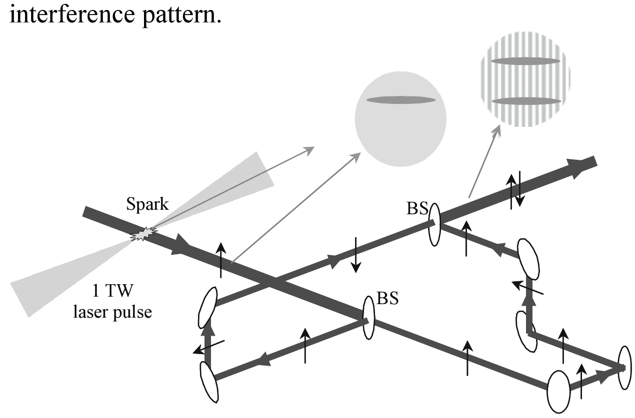

figure 3: Schematic representation of the folded wave interferometer. The arrows indicate the position of the spark in the beam (up or down). BS = beamsplitter.

The phase difference is a function of the electron density (1) and from (1) radial and axial profiles of the electron density as a function of position in the plasma can be calculated.

$$\Delta\varphi = \frac{\pi e^2}{\omega^2 \lambda_0 m_e \varepsilon_0} \int_0^L n_e dl \qquad (1)$$

The probe beam is led over a motorized precision delay stage. By changing the delay of the probe beam the plasma can be probed at different times and the evolution of the spark in time can be monitored. The pulse length of the probe beam is 25 fs. This determines the resolution of the FWI.

The FWI is computerized. The system can be programmed so that at fixed timesteps pictures of the interference patterns are made. Analysis of the interference patterns is done by an IDL 5.5 (Research Systems Inc.) computer program giving directly the axial and radial electron density profiles.

Electro-optic pulse characterization

After switching, the high voltage pulse will have a risetime of the order of picoseconds. Electro-optic sampling is capable of resolving electric fields with subpicosecond precision. This method was first used for measuring bunch-lengths of relativistic electron bunches [8]. The electric field of an electron bunch or travelling high voltage pulse on a conductor induces a birefringence in a non-linear crystal (Pockels effect) that is placed near the bunch/conductor. If this birefringence is probed with an ultra-short linearly polarized laser it will become elliptically polarized. The ellipticity-change is a function of the electric field and by varying the delay between the laser pulse and the crossing high voltage pulse, the electric field and thus the pulse length and shape of the high voltage pulse can be measured. As non-linear medium we will use a cubic, optically isotropic ZnTe crystal. The induced phase change is given by (2):

$$\Delta\varphi = \frac{\omega}{c} n_0^3 r_{41} E l \qquad (2)$$

with n_0 the refractive index @ 800nm of ZnTe (2.85), r_{41} the electro-optic coefficient (4.3 pm/V) and l the length of the crystal (0.2 mm). The induced phase change depends on the thickness of the crystal and the electric field strength. The time resolution is determined by the time it takes a laser pulse to traverse the crystal.

The actual measurement setup will be the same as described in [9] and is given in figure 4. The incoming linearly polarized laser pulse will be elliptical after it has probed the ZnTe crystal. Optical biasing takes place by the quarter wave plate, which converts the elliptical polarization to linear again, and the polarizing beam splitter (Wollaston prism) that dissolves it into two linearly polarized pulses. Measuring the difference between the two linearly polarized components with photo diodes gives the phase change.

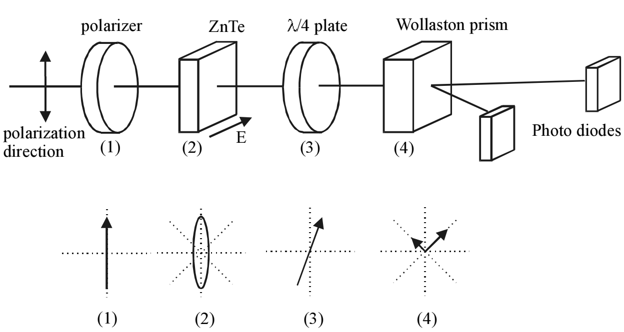

figure 4: Electro-optical setup with its components. The bottom part gives the polarization directions after probing the different components.

A data-acquisition system with an integrated delay stage will be installed for easy measuring and analysis of the high voltage pulses.

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 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. A folded wave interferometer is developed to monitor the spark evolution (electron density) with a resolution of 25 fs. Electro-optic pulse characterization will be used to resolve the switched high voltage pulse with ps resolution.

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