A 1 GV/M LASER-TRIGGERED COMPACT ACCELERATOR

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Abstract

A novel design for a compact multistage electron injector is presented. The new method should exceed state of the art photocathode rf guns for the production of high-brightness, ultra-short electron bunches by one order of magnitude. It is based on 1 GV/m stepwise acceleration using a switched 2 MV, 1 ns pulsed power supply. Switching the consecutive acceleration stages on ps timescales is accomplished by instantaneous ionization of laser-triggered spark-gaps. Colliding pulses are used to double the acceleration field and eliminate the magnetic deflection field in the acceleration gaps. Using this scheme, an average field of over 600 MV/m is produced. Simulation results using the GPT code show that it is possible to generate 12 MeV, 100 pC, 0.7 kA bunches with an emittance below 1π mm mrad and a length of 100 fs, without magnetic compression. The ultra-short electron bunches can be used to produce short XUV/X-ray pulses or can be further accelerated in a laser wakefield accelerator.

1 INTRODUCTION

The volume that an electron bunch occupies in the six dimensional position and momentum space determines the focusability in the longitudinal and transverse directions of a bunch. It is closely related to the beam brightness, defined as the current density per unit solid angle and per unit relative particle energy spread [1]. Because the six dimensional volume of a bunch can only increase, the brightness of an injector determines the maximum charge density that can be achieved after acceleration and focusing. For this reason, high brightness electron injectors are essential for demanding applications such as colliders and free-electron lasers (FEL) based on the self-amplified spontaneous emission (SASE) process.

The conventional method for the production of high-brightness electron beams is the photocathode RF gun. The produced bunches do not yet have the required charge density and are therefore first accelerated to sufficiently high energies and subsequently compressed magnetically to a bunch-length of the order of 100 fs. However, magnetic compression gives rise to radiative collective effects, which spoil the emittance and thus the brightness [2].

At Eindhoven University of Technology (TU/e) we have therefore adopted a different strategy. We aim at the production of electron bunches with a significantly higher brightness without magnetic compression: 100 fs, 100 pC

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with a normalized emittance below 1π mm mrad [3,4]. These high-brightness ultra-short electron bunches can be used to produce short XUV/X-ray pulses and are ideally suited for further acceleration in a laser wakefield accelerator.

A new design is based on 1 GV/m stepwise acceleration using a switched 2 MV, 1 ns pulsed power supply. The electrons are photo-excited from a metal cathode by a fs-laser. Picosecond switching of consecutive acceleration stages is accomplished by instantaneous ionization of laser-triggered spark-gaps. Colliding pulses are used to double the acceleration field and eliminate the magnetic deflection field in the acceleration gaps. A schematic 3D view of the accelerator with 3 stages is shown in Figure 1.
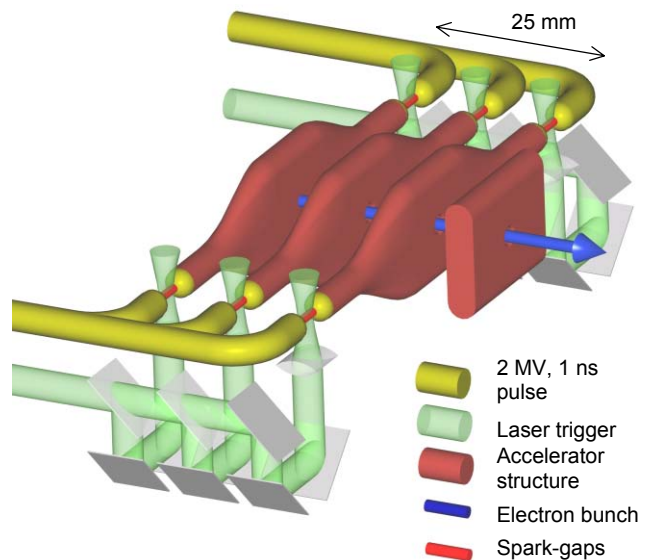

Figure 1: Schematic of the compact 1 GV/m colliding pulse accelerator.

2 SINGLE STAGE ACCELERATOR

The design of the multi-stage accelerator builds on the design of a single-stage accelerator, as briefly described in this section. Figure 2 shows the typical set-up for a single-stage high-voltage pulsed accelerator, consisting of a copper cathode and anode. A 2 MV, 1 ns pulse-generator supplies a 1 GV/m acceleration gradient across the 2 mm acceleration gap of this diode. This extreme field-strength, an order of magnitude higher than state-of-the-art rf accelerators, is possible because it is applied for only 1 ns, which is too short for electrical breakdown to occur. The voltage pulse can be created using a Tesla transformer as demonstrated by [5]. Other techniques

allowing a higher repetition rate, for example based on charging transmission lines in parallel and switching them in series, are currently being investigated.
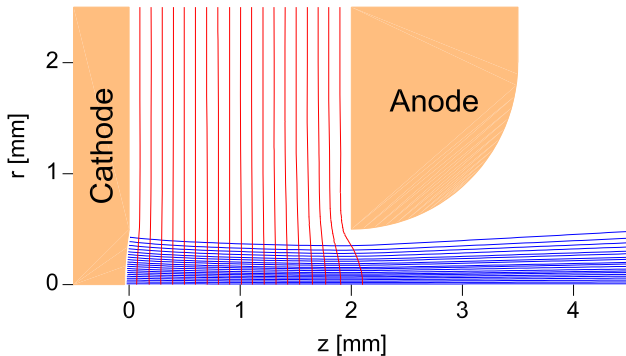

Figure 2: Diode with potential lines and sample particle trajectories.

To create high-brightness electron bunches, a femtosecond laser is used to photo-emit kA electron bunches from the cathode surface. The cathode is curved to produce a transverse focusing field. The aperture acts as a defocusing lens, counteracting the curved cathode focusing effect.

The main difference of this device compared to rf-accelerators is the fact that the 1 GV/m acceleration field allows the kA electron bunches to be accelerated without significant deterioration due to space-charge effects. This eliminates the need for downstream magnetic compression and prevents the accompanying emittance growth.

The aperture in the anode needs to be kept as small as possible to prevent the field from leaking out of the gun and thereby lowering the acceleration field. This gives rise to highly non-linear transverse fields where the beam passes through the iris. These non-linear fields potentially deteriorate the transverse emittance and hence the brightness of the bunch. However, by choosing the correct geometry these non-linear transverse fields can actually be used to our advantage to compensate the effect of the non-linear space-charge forces in a flat-disk shaped bunch [6].

In General Particle Tracer (GPT) [7,8] simulations, the single stage device shown in Figure 2 produces 100 pC, 2 MeV electron bunches with full-with-half-max of 73 fs and a root-mean-square emittance of 0.4 π mm mrad. The peak-current is 1.2 kA.

3 MULTI-STAGE ACCELERATOR

The single stage high-voltage pulsed-accelerator described in section 2 cannot be used 'as-is' as high-brightness electron injector because the exit beam energy of 2 MeV is too low. The energy of the bunch can be increased by the addition of a conventional rf accelerator, leading to a DC/RF acceleration scheme [9]. Another solution is to increase the voltage of the pulsed-power supply from 2 MV to over 5 MV. We are currently studying the technological feasibility of such a device.

The option to increase the bunch energy while conserving the beam-brightness discussed in the remainder of this paper makes use of high-power laser technology to ionize gas on timescales below a ps. Combined with a high-voltage pulsed power supply, several consecutive 1 GV/m acceleration stages can be switched to provide stepwise 1 GV/m acceleration to energies over 10 MeV.

3.1 Principle

The principle of a two-stage accelerator is shown schematically in Figure 3. A high-voltage pulse, with a duration of 1 ns to avoid breakdown, creates an acceleration field between the cathode and the iris with a strength of the order of 1 GV/m. This semi-DC field is present when, in the left plot, a kA electron bunch is extracted from the cathode by a sub-picosecond photo-excitation laser. The electrons are accelerated in the 1 GV/m field, maintaining sub-picosecond bunch-length and good emittance due to the high acceleration field.

During the passage of the electron bunch through the iris, an other laser is fired to ionize the spark-gap, such that the voltage pulse reaches the iris precisely at the time when the electron bunch is completely inside the iris. Being in the iris in a near zero-field region, the bunch quality is not affected by the switching. When the electrons exit the iris, they are accelerated in a 1 GV/m field again to double the energy compared to a singe stage. The acceleration process can continue even further when more electrodes, each with its own laser-triggered spark-gap, are added.
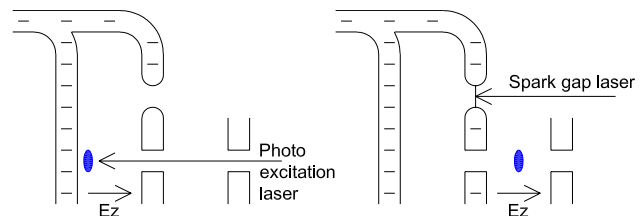

Figure 3: Two-stage accelerator. Left plot: Electrons are photo-extracted from the –2 MeV cathode and accelerated in a 1 GV/m field. Right plot: The spark gap is laser-ionized and the electrons are accelerated again, using the same power supply.

However, the high-voltage pulse traveling in the conductor creates a magnetic field, deflecting the electron bunch. This makes a practical design very complicated. To compensate this undesired magnetic field in the path of the electron bunch, we propose to feed the high-voltage pulse into the accelerator from two sides. The spark-gaps need to be triggered such that each pair of voltage-pulses reach the irises at the same time from opposing directions. This cancels their magnetic field, while simultaneously doubling the acceleration field.

3.2 Operational requirements

The requirement that good bunch quality is maintained during the passage through the irises imposes strong

restrictions on the parameter range in which this device can be operated: There must be a zero-field region inside the irises and the bunch-length must be much shorter than the thickness of the iris because the bunch needs to be completely in the zero-field region during switching. Furthermore, the risetime of the voltage-pulse must be shorter than the passage-time of the bunch through the iris and the passage-time of the bunch through the iris must be longer than the traveling time of the HV pulse over the iris.

When we assume a 2 MV power-supply, the field doubling technique can be used to accelerate an electron bunch to 12 MeV in 3 stages of 4 MV each. A desired peak field of 1 GV/m requires the acceleration gap in each stage to be 4 mm. Because there is no acceleration field inside the irises, their width must be kept as short as possible to maintain a high average acceleration field. As a result, the thickness of the irises must be of the order of 4 mm or less. This in turn leads to an iris radius of less than 0.5 mm, and thus a bunch radius of less then 0.5 mm. Using this scheme, an average acceleration field of over 600 MV/m can be produced. Furthermore, the bunch length cannot be more than about a ps and the risetime of the laser-triggered spark-gap also needs to be of the order of a ps, to keep the head and the tail in the zero-field region during switching.

In a typical laser-triggered high-voltage spark-gap, a laser-pulse weakly ionizes a gas holding voltages of over one MV. This in turn causes a small current, which heats the gas and increases the conductivity. The process continues until there is no voltage difference over the gap and the switch can be considered closed. Unfortunately, this process cannot be used because it is too slow, of the order of 100 ps, and causes too much jitter between the laser and the time when full conductivity is reached. For this reason, we propose to use a high-power laser to ionize sufficient gas in the spark-gap instantaneously, reducing both the switching time and the jitter to the ps level.

3.3 Simulation results

Fully self-consistent simulations for the described compact accelerator are very complicated due to the very short timescales that need to be taken into consideration and the inherent 3D nature of the device. However, detailed FDTD pulse-propagating simulations in 3D indicate that it is possible to transport pulses with a risetime of one ps into the accelerating electrodes, assuming instantaneous full conductivity in the laser-triggered spark-gaps. Furthermore, the circular irises produce a near cylindrically symmetric field in the path of the electron beam. This justifies our initial approach to simulate the fields of the high-voltage pulses as a cylindrically symmetric electrostatic problem.

In the simulations, a 100 pC electron bunch is photo-extracted from the surface with a 50 fs FWHM temporal profile. The initial thermal emittance is assumed to be 0.1 π mm mrad for a hard-edge radius of 0.25 mm.

The main GPT simulation results for the multi-stage 1 GV/m compact accelerator are shown in Table A, side-by-side with the single-stage and a DC/RF scheme [9]. The simulations include all non-linear space-charge effects, given the cylindrically symmetric electrostatic approximation.

Clearly, all three options presented produce 'world-class' bunches compared to rf photogun technology. Although the DC/RF scheme is a new and interesting approach, it is clear that it cannot compete with the presented laser-switched multi-stage scheme. The multi-stage scheme preserves the beam quality of the 1 GV/m single-stage accelerator much better, mainly because the first stage accelerates to double the energy due to the colliding pulses resulting in less bunch-lengthening. This results in a near 1 kA electron bunch with a final emittance far below 1 π mm mrad.

Table A: GPT simulation results for the laser-switched multi-stage accelerator. The single-stage and DC/RF schemes are shown as comparison.

Parameter	1 Stage	DC/RF	Multi stage	Unit
Energy	2	10	12	MeV
Charge	100	100	100	pC
Length	73	200	110	fs fwhm
Emittance	0.4	1.0	0.6	π μm
Current	1.2	0.4	0.7	kA

4 CONCLUSION

The beam parameters at the exit of the proposed compact multi-stage laser-triggered accelerator are very promising. Simulation results using the GPT code show that it is possible to generate 12 MeV, 100 pC, 0.7 kA bunches with an emittance below 1 π mm mrad and a length of 110 fs, without magnetic compression. Further study is required to convert this idea into a practical design.

5 REFERENCES

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