A HIGH-BRIGHTNESS PRE-ACCELERATED RF-PHOTO INJECTOR

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Abstract

At Eindhoven University of Technology a project has started aiming at the production of 100 fs, 100 pC electron bunches, with an emittance below 1 π mm mrad. These bunches are compatible with the requirements for a plasma wakefield accelerator or can be used to generate ultra-short XUV/X-ray pulses. The device currently under construction consists of two stages: A photo-excited DC 1 GV/m pre-accelerator, directly followed by a state-of-the-art S-band rf-booster. The field in the first stage is sufficiently high to avoid space-charge explosion at low energies. Therefore magnetic compression is not needed and this in turn eliminates undesirable radiative collective effects, which spoil the emittance. The 1 GV/m field is created in a 2 mm acceleration gap, powered by a 2 MV, 1 ns pulse generator. The second stage increases the energy to 10 MeV using a 100 MV/m 2.5 cell standing wave cavity with axial symmetric incoupling. Simulation results using the GPT code for the combined setup are presented.

1 INTRODUCTION

Progress in accelerator physics relies on injectors capable of delivering short, high brightness pulses [1]. Sub-picosecond electron bunches are required for injection into plasma-based accelerators and beam brightness is an important quality for collider and X-ray self-amplified spontaneous-emission free electron laser (SASE FEL) experiments. The desired brightness places a high demand on the transverse beam quality, which is expressed in terms of the normalized emittance.

At present the favorite method for the generation of high brightness, low emittance electron bunches is the photo-cathode rf gun. This device delivers bunches with a typical length of a few picoseconds. To achieve the current density required by many applications, the bunches are first accelerated to relativistic energies, thereby reducing the space-charge forces. They are subsequently magnetically compressed to sub-picosecond lengths. Unfortunately, however, magnetic compression gives rise to radiative collective effects, which spoil the emittance [2].

At Eindhoven University of Technology (TUE) we have therefore adopted a different strategy. We aim at the production of 100 fs, 100 pC electron bunches with a normalized emittance below 1 π mm mrad without the need for magnetic compression [3, 4]. The bunches are generated by photoemission from a metal cathode and accelerated to 2 MeV in a 1 GV/m pulsed electrostatic field [5]. An extremely high field is used to achieve relativistic velocities as quickly as possible, because space-charge induced emittance growth and bunch lengthening occur mainly at non-relativistic energies. The bunches are further accelerated in a conventional rf accelerator.

The most important issue in the design of this system has been space-charge, as 1 kA peak current is transported from the cathode to relativistic energies without compression. For bunches with the desired parameters, the bunch length is much smaller than the radius, i.e. the ‘pancake’ geometry. In this case the nonlinearity of the radial space-charge field is much more pronounced than in a ‘cigar’ geometry and can lead to undesirable emittance growth. To minimize beam deterioration, the nonlinear space-charge force is canceled by highly nonlinear radial field components of the geometry in a nonlinear electrostatic emittance compensation scheme [6].

In this paper we will present both DC and rf accelerator stages and a study of the beam dynamics using the General Particle Tracer (GPT) code.

2 PULSED DC PHOTOCATHODE

The TUE pulsed DC photocathode consists of a hollow copper cathode and an anode with a circular aperture, shown in Figure 2. The cathode and anode are separated by 2 mm and the radius of the anode aperture is 0.5 mm. A 2 MV, 1 ns pulse generator, an upgrade of the device used in [5], supplies the 1 GV/m gradient across the 2 mm acceleration gap of this diode. This extreme field strength - almost an order of magnitude higher than in state-of-the-art rf accelerators - is possible because it is applied during only 1 ns, which is too short for electrical breakdown to occur.

Synchronization of the photo-excitation laser pulse with the 1 ns flat top of the 2 MV pulse is to be achieved by laser triggering of the spark gap in the HV pulser. The photo-excitation laser pulse is injected on-axis and has a 50 fs full-width-at-half-maximum (FWHM) gaussian temporal profile and a 0.9 mm diameter gaussian radial profile. The choice of an initial beam radius of 0.45 mm is a compromise between bunch lengthening due to space-charge at small initial radius and increase of the thermal (or initial) emittance at large initial radius. The design simulation parameters are listed in Table A.

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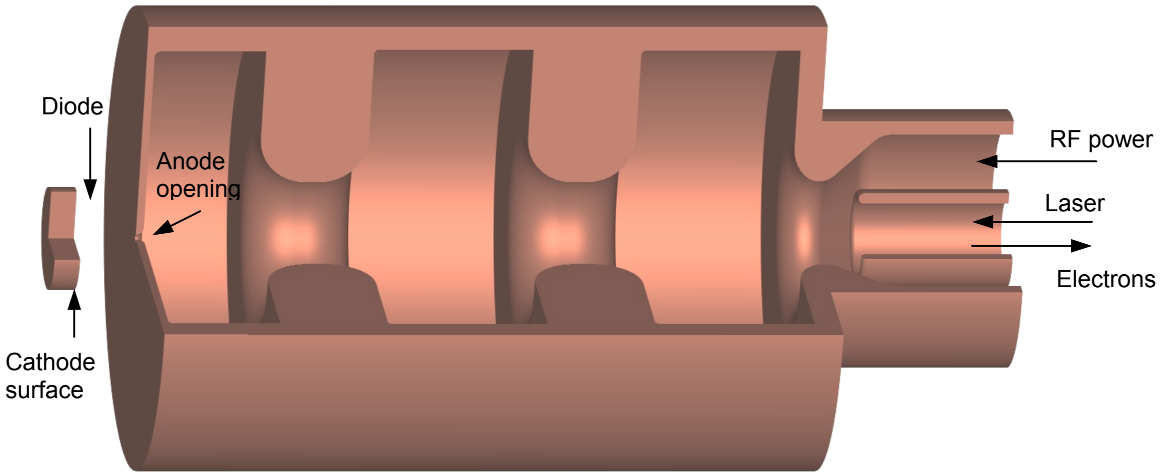

Figure 1: 3D schematic of the rf booster. The diode is shown, not to scale, on the left. The rf power enters the cavity between the inner and outer conductor shown at the right. The inner conductor is hollow to allow the electron beam to pass through and is also used to send the laser beam through the anode opening onto the cathode surface of the diode.

The aperture in the anode acts as a negative lens and is kept as small as possible to prevent the field from leaking out of the gun and thereby lowering the acceleration field. As a result the outer radial part of the bunch passes through the anode at a very small distance from the inner surface of the aperture. Since deviations from ideal lens behavior are maximal at the electrode surface, it is unavoidable that the bunch is subjected to highly nonlinear radial fields. This effect is used to counteract beam deterioration due to nonlinear space-charge forces [6].

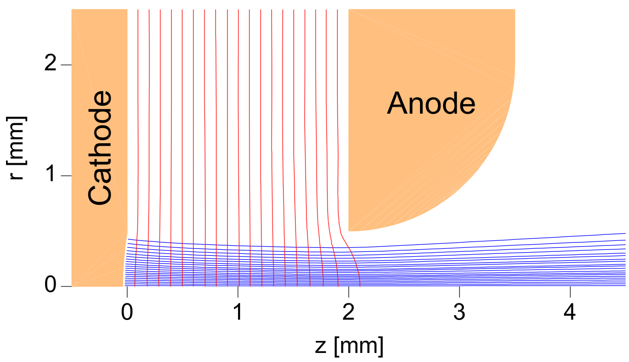

Figure 2: Diode with potential lines and sample particle trajectories.

3 RF BOOSTER

The diode is directly followed by a 2½-cell rf cavity to prevent beam deterioration in a drift space. The 100 MV/m, S-band standing wave cavity increases the bunch energy to a stable 10 MeV.

We find that the beam has a laminar flow in the entire beamline. Throughout the acceleration process the bunch length is much smaller than the bunch radius, i.e. the bunch maintains the shape of a flat disk.

Table A: Diode and rf-booster parameters.

Parameter	Value
Bunch charge	100 pC
Initial emittance	0.2 π mm mrad
Beam radius	0.45 mm, cut-off gaussian
Laser pulse length	50 fs, gaussian
Cathode curvature radius	3 mm, hollow
Diode voltage	2 MV
Gap length	2 mm
Diode nominal field	1 GV/m
Anode aperture	0.5 mm
Frequency of booster	2998 MHz
Klystron power	10 MW
Solenoid strength	0.42 – 0.52 T

The booster was designed as an adapted version of the DESY 1.3 GHz axial power coupler [7]. This coupling technique ensures that the axial symmetry is not broken by side-coupling and allows easy positioning of a focusing solenoid. The booster with the diode is shown in Figure 1. The photo-excitation laser and the produced electrons pass through the inner conductor of the coupler and the rf power is transferred by the outer coaxial structure.

The matching of the electrostatic diode to the 2½-cell rf cavity is not optimal. The main reason is the fact that the bunch exits the diode with divergence, while the rf-booster ideally starts with a parallel beam. Because the bunch will lengthen substantially in any drift space or matching section after the diode, the best results are obtained when, as shown in Figure 1, the diode and rf-booster are positioned as close to each other as possible.

RF bunch compression is not possible at 3 GHz for a bunch of only 30 micron length. The transverse dimensions of the bunch are controlled by a solenoid over the entire rf cavity and a bucking coil is used to have zero field on the cathode surface.

4 SIMULATION TOOLS

Simulations for the design of the diode were performed using the General Particle Tracer (GPT) simulation package [8, 9]. GPT is a commercially available time-domain 3D particle tracking code developed for the design of accelerators and beam lines. The differential equations for the particle trajectories are solved using a fifth order embedded Runge-Kutta method.

The 2D space-charge model of GPT was used, instead of the standard 3D point-to-point model, because the system is cylindrically symmetric. For the simulations presented in this paper, GPT was used in combination with the POISSON [10] set of codes to calculate the field map of the diode and the booster. The effects of image charges in the cathode and wakefields in the anode are not included in the simulations. A straightforward estimate shows that the field associated with image charges at the cathode surface is negligible compared to the 1 GV/m acceleration field.

5 SIMULATION RESULTS

An external solenoid with a maximum field of 0.42 – 0.52 T results in the best overall beam parameters. By varying the solenoid strength a divergent, parallel or focused beam can be generated. A solenoid strength of 0.46 T results in a nearly parallel beam, as shown in Figure 3. More focusing is possible at the cost of bunch lengthening. For better planning of future experiments, the beam is tracked to 500 mm after the cathode.

The resulting beam has an emittance of 0.93 π mm mrad and a bunch length of 209 fs FWHM at 200 mm, as shown in Figure 4. The energy spread is below 2% with a peak current of 0.4 kA.

Further increasing the strength of the solenoid (and bucking coil) to 0.52 T results in a waist at 0.8 m with a radius below 0.2 mm. At the waist the emittance is lowered to 0.8 π mm mrad due to emittance compensation [11]. Unfortunately, a price is paid in terms of bunch lengthening to 350 fs at the waist.

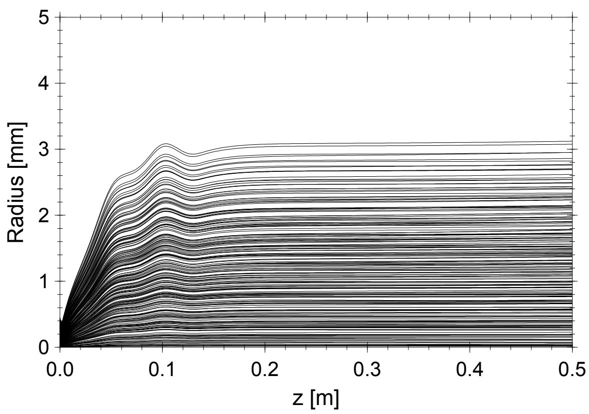

Figure 3: Particle trajectories for a parallel beam in the complete set-up. 200 sample particles are used in the simulation.

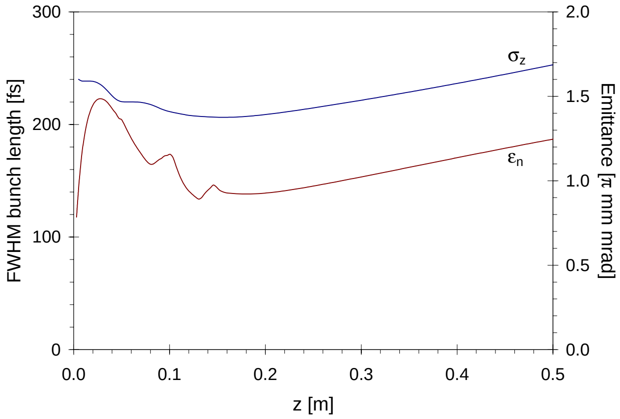

Figure 4: Bunch length and emittance evolution for a parallel beam.

6 CONCLUSION

With a 1 GV/m diode field, directly followed by a 2½ cell rf booster accelerator, it is possible to produce 200 fs pulses with a divergent bunch, a nearly parallel beam and a small spot with an emittance below 1 π mm mrad, depending on external magnetic focusing. These bunches fail to meet the original goal of 100 fs FWHM bunch length. However they still have a world-class high-brightness and the device currently under construction at TUE will for the first time demonstrate the concept of a pre-accelerated beam in a 1 GV/m field combined with a BNL-like rf accelerator.

To reduce the bunch length to below 100 fs, the most straightforward option is to use a 5 MV HV pulser to create the 1 GV/m field. This will not change the concept of the device and will accelerate the bunch to 5 MeV. The defocusing effect of the anode is significantly reduced due to the higher energy, the beam is better matched into the rf-booster and will lengthen less in the first few critical millimeters.

7 REFERENCES

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